HIGH PERFORMANCE CONCRETE FOR TRANSPORTATION STRUCTURES

FINAL REPORT
FHWA/OK 98(07)

by

THOMAS D. BUSH, JR.
and
BRUCE W. RUSSELL
Co-Principal Investigators
and
SEAMUS F. FREYNE
Research Assistant

SEPTEMBER 1998

sponsored by

OKLAHOMA CENTER FOR THE ADVANCEMENT OF SCIENCE AND TECHNOLOGY
and
OKLAHOMA DEPARTMENT OF TRANSPORTATION RESEARCH AND DEVLEOPMENT DIVISION
in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION

conducted at

FEARS STRUCTURAL ENGINEERING LABORATORY
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE
UNIVERSITY OF OKLAHOMA, NORMAN, OKLAHOMA

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. FHWA/OK 98(07)	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE High Performance Concrete for Transportation Structures		5. REPORT DATE September 1998 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Thomas D. Bush, Jr., Bruce W. Russell, Seamus F. Freyne		8. PERFORMING ORGANIZATION REPORT
9. PERFORMING ORGANIZATION NAME AND ADDRESS Fears Laboratory, Univ. of Oklahoma 303 E. Chesapeake Norman, OK 73019		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 2112-96-01
12. SPONSORING AGENCY NAME AND ADDRESS Oklahoma Department of Transportation Office of Research 200 N.E. 21st Street, Room 2A-2 Oklahoma City, OK 73105-3204		13. TYPE OF REPORT AND PERIOD COVERED Final Report Jan. 1996 - Sept. 1998 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES In cooperation with the Federal Highway Administration, US Department of Transportation.		

16 . ABSTRACT

Use of high performance concrete has tremendous potential for improving economy and long term durability of structures. The State of Oklahoma has an abundance of high quality aggregates that are necessary for the production of high strength/high performance (HSHPC) concrete. This research report is intended to help the state harness the economic advantages of constructing Oklahoma's infrastructure with HSHPC.

The research program systematically examined locally available materials to determine those most suitable for production of HSHPC in Oklahoma, and tested mixture designs to see the effects of interactions of those materials. The effects of changing cement source and type, fine aggregate grading, and coarse aggregate type and grading were studied. Concrete mixtures were tested where only a single material (for example, cement) was varied while all others were held constant. Materials included in the testing program were Type I, II, and III cements from various suppliers, fine aggregates with two different fineness moduli, and four types of coarse aggregates in two gradings. A study was then conducted to examine the effects of varying total cementitious materials content, addition of supplementary cementitious material (Class C fly ash), and varying water to cementitious material ratio on properties of HSHPC.

The research established that Oklahoma has outstanding locally available materials capable of producing HSHPC with compressive strengths of 100 MPa (14,000 psi) and greater. Several cements were found suitable, although some variations in concrete strength as a result of changing the cement were observed. Crushed limestone, rhyolite, and granite coarse aggregates all performed well in HSHPC; sandstone river gravel was only suitable for producing concretes with strengths up to about 70 MPa (10,000 psi). Exceeding a total cementitious material content of about 500 to 550 kg/m^3 resulted in little to no additional strength benefit. Replacement of up to 20 percent of the portland cement with Class C fly ash reduced early strength, but improved workability and allowed use of a lower water to cementitious material ratio, effectively increasing long term compressive strength.

17. KEY WORDS **high performance concrete, coarse aggregates, cements, mixture proportions**	18. DISTRIBUTION STATEMENT This report is available from the Office of Research, Oklahoma Department of Transportation.		
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 53	22. PRICE

SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					*Approximate Conversions from SI Units*				
Symbol	When you know	Multiply by	To Find	Symbol	Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yd
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		AREA					AREA		
in^2	square inches	645.2	square millimeters	mm	mm^2	square millimeters	0.00155	square inches	in^2
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectares	ha	ha	hectares	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME					VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.2642	gallons	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		MASS					MASS		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

HIGH PERFORMANCE CONCRETE FOR TRANSPORTATION STRUCTURES

CHAPTER 1

OVERVIEW

1.1 Introduction

High Performance Concrete (HPC) originated in the development of high strength concrete. In developing high strength concrete (HSC) other desirable concrete properties were produced such as low permeability, increased density, lessened drying shrinkage, and lower creep. These advances in concrete technology recognizing improved concrete properties, including strength, have led to use of the more inclusive term, high *performance* concrete.

Normal strength concrete has a long, proven history in structural applications; however, only in the last two decades has HSC been developed and used commercially. Initially, HSC was developed to support large axial forces in columns of high-rise buildings. In 1972, 9000 psi concrete was used in the 50 story Mid-Continental Plaza Building in Chicago, Illinois. In 1989, columns of 14,000 psi strength, and one test column of 17,000 psi strength, were used in the 225 W. Wacker Drive building in Chicago (Moreno 1990). Today, HS/HPC is frequently used in construction of high-rise structures, most notably in Chicago, New York, Houston, and Seattle. Economic benefits have driven the use of HS/HPC in high-rise buildings. High strength concrete can have twice the unit cost of normal strength concrete, but strength can readily increase by a factor of four. More recent studies indicate that HS/HPC also has economic benefits in low- and medium-rise buildings (Smith and Rad 1989). It was estimated that column construction costs can be reduced from 25-45 percent for buildings in the range of 5-15 stories.

Recent literature clearly indicates significant economic benefits by using HS/HPC in highway bridges (Russell 1994). HS/HPC can allow longer bridge spans, or alternatively, fewer girders per span with the net effect of reducing overall construction costs. HS/HPC's also have the desirable effect of improving the life span of a bridge structure by reducing permeability, thereby helping prevent deicing salts from penetrating a bridge structure.

One hurdle to widespread implementation of high strength HPC is that the engineering properties (strength, etc.) of hardened concretes depend largely upon the suitability of locally available materials. Recently, the Louisiana DOT tested three pretensioned girders that were intended to attain concrete strengths of 10,000 psi. However, because of the poor quality of locally available aggregates, the maximum compressive strength attained was roughly 9800 psi at 28 days. On the other hand, research from the Texas DOT indicates little trouble making concrete with strengths in excess of 10,000 psi (Carrasquillo 1986, Ralls and Carrasquillo 1997). From these experiences, it is evident that high strength HPC must be developed at the local level, using locally available aggregates.

In 1992, a survey of the precast concrete industry was conducted concerning the use and reliability of high strength concrete (Dolan and LaFraugh 1993). From the survey, the industry has apparently stagnated at 8500 psi for a maximum concrete strength. Reluctance to develop higher strength concrete has centered on the ability to reliably produce concretes exceeding 8500 psi. A secondary, but important, conclusion was developed from the survey, that nationwide, pretensioned concrete bridge girders represented the state-of-the-industry. Furthermore, bridge girders may serve as the best product to showcase the ability to produce high strength concrete. Therefore, this research is very timely, to drive further increase in concrete strength through the production of pretensioned concrete bridges.

1.2 Production of HPC

Development and production of concrete has traditionally relied on a trial and error approach to develop extensive knowledge of local materials. A systematic approach must be taken for HS/HPC, and accounting for properties of local materials is critical to success (Domone and Soutos 1994). Each of the constituent materials can greatly affect the strength and other engineering properties of hardened concrete, especially when strengths exceed 10,000 psi. Key material factors to evaluate are cement, water to cementitious material ratio, coarse and fine aggregates, and mineral and chemical admixtures.

The quality and source of cement are important to produce high strength concrete (Chicago Committee 1977). In fact, variations in cement can affect compressive strength more than any other constituent material. HPC mixes typically contain more cement than normal strength concrete, with the amount dependent on the desired performance criteria. Research has shown that there is an optimum range beyond which increasing cement content will no longer increase strength.

The ratio of water to cementitious material, usually referred to as the w/c ratio, also has a major impact on strength and durability. To reflect the content of mineral admixtures (m) in addition to cement (c), the w/cm ratio is used. Lower water volumes and lower w/cm values generally promote higher strength and lower permeability. An upper limit of about 0.40 is usually set for HS/HPC, while normal concrete uses w/c ratios up to about 0.50. A lower limit of approximately 0.27 is recognized as necessary to ensure sufficient water is available for hydration (Peterman and Carrasquillo 1986).

The selection of coarse aggregates requires careful consideration for HS/HPC. For HS/HPC, failures often occur in the aggregate itself (Aïtcin and Neville 1993) and at the aggregate-mortar interface. Characteristics of the coarse aggregate can also have considerable influence on mixing water requirements to achieve the desired consistency. The maximum size of the coarse aggregate (MSA) affects the strength that can be obtained. Maximum aggregate sizes of about 3/4 in. can be used to produce HPC with compressive strengths of about 8000 psi. Smaller maximum size aggregates (3/8 to ½ in.) are necessary to produce strengths in excess of 9000 psi (Peterman and Carrasquillo 1989). In addition, crushed rock tends to produce higher strength mixes than rounded gravel. Aggregates such as crushed limestone result in better bond between mortar and aggregate, which leads to increased strength.

Fine aggregate (sand) does not have as great an influence as coarse aggregate on producing HPC. However, coarser sands may be desirable because they could reduce mixing water demands and facilitate lower w/cm ratios. Coarser sands can also improve the density of concrete, thereby improving both strength and durability. Furthermore, coarser sands reduce the "stickiness" inherent to mixes that contain large amounts of fines (cements and sands), promoting better workability while the concrete is "wet", usually referred to as the "plastic state". A recommended range of sand fineness modulus for high strength HPC is 2.70-3.20 (Peterman and Carrasquillo 1986). If available sands are too fine, coarser materials should be blended to increase the fineness modulus (ACI 363R 1992).

Mineral and chemical admixtures are essential components of HS/HPC. The most common mineral admixtures are fly ash, silica fume, and blast furnace slag. These mineral admixtures are all by-products of heavy power and/or steel industries. Fly ash is commercially produced in Oklahoma as a by-product to electrical power. Mineral admixtures are used as partial replacement for cement, and all possess pozzolanic and/or cementitious properties. Fly ash promotes increased strength, increased elastic modulus, decreased permeability, reduced creep and shrinkage, improved workability and finishibility, and reduced heat of hydration (Tikalsky et al. 1988).

Silica fume produces similar results to fly ash; however, silica fume is a much finer material and its use increases compressive strength more rapidly at early ages than other mineral admixtures. Silica fume also leads to reduced permeability and higher durability. Tests have shown that mixes with silica fume and w/cm ratios less than 0.30 can make concrete virtually impermeable to water and to chloride ions (Fiorato 1989). Drawbacks of silica fume include its high cost and tendency to darken the color of the concrete. Another admixture, metakaolin, has been found to produce results similar to silica fume without discoloration (Caldarone et al. 1994).

Chemical admixtures are necessary to improve workability, control set time, and entrain air. High range water reducers (HRWR's), commonly called superplasticizers, are essential to producing workable HPC. In normal strength concrete, water is the primary lubricating agent that allows the concrete to be placed efficiently. In HS/HPC, w/c ratios are too low to allow placement of the concrete without the use of HRWR's. These admixtures also enhance hydration and improve strength through more uniform dispersion of the cement particles. Air entraining admixtures may be used to improve freeze-thaw resistance, promoting better durability. Entrained air has the negative effect of decreasing strength. However, it is possible that minimum air content limits can be reduced for HPC due to inherently better air void parameters (Fiorato 1989, Peterman and Carrasquillo 1986).

1.3 Opportunities and Longer Term Objectives

It is clear that HPC has tremendous economic and structural benefits. Engineering projects in much of the US have been slow to seize these opportunities (Lane and Podolny 1993). As demonstrated in numerous research projects, the technology to produce HS/HPC is readily available; however, this technology does not directly translate to all situations. The technology must be adapted, through a comprehensive research study, for the materials that are locally available for production of HPC in Oklahoma. Fortunately, Oklahoma has some excellent sources of high quality limestone aggregates. But available materials must be assessed to identify desirable characteristics and screen out unsuitable materials. Engineering and construction properties must also be determined and documented for designers.

To instill confidence in the technology, production capability of HS/HPC should be demonstrated. Baseline behavior of structural members made from the material must be established. Results of this research will provide valuable information and experience that can be built upon to develop HS/HPC mixes optimized for other applications such as pavements and bridge decks. The research will also provide fundamental behavioral information for investigations focused on other aspects of behavior of HS/HPC members, and for development of other HS/HPC products.

1.4 Research Objectives

The State of Oklahoma is blessed with an abundance of high quality aggregates that are necessary for the production of high strength/high performance concrete. Therefore, the research described herein is intended to help the state harness the economic advantages of constructing Oklahoma's infrastructure with HS/HPC. The general objectives of the research are listed as follows:

1. To develop HS/HPC with strengths exceeding 14,000 psi using locally available materials.
2. To measure and identify material properties that significantly affect the strength and performance of concrete.
3. To measure and identify material properties of the constituent materials that can improve the strength and performance of concrete.
4. To optimize engineering and construction properties of HS/HPC mix designs, considering cost, workability, and engineering properties of the hardened state.
5. To develop pathways for technology transfer from research and the university to engineers, architects, contractors and ready mixed concrete operators.

For "real world" structural applications, HPC must meet dual requirements. HS/HPC must be strong, durable, not prone to excessive creep or shrinkage, and embody all other required engineering properties while simultaneously being "user friendly." In other words, it must be easy to place and easy to work while wet. If, during construction, a ready mix truck arrives at the jobsite with concrete that is unworkable, the foreman's cry of "add five (gallons of water)" will negate the positive effects of pre-engineering the concrete material. Therefore, obtainable performance properties from a strict theoretical standpoint must be balanced against basic requirements to accelerate HPC's acceptance as an alternative to normal strength concrete mixtures. Performance properties of the end product should not be obtained at the expense of properties which strongly influence HPC's field implementation, namely, placeability, time to set, and cost. In simplest terms, if a high performance concrete mix is not practical to place and is too costly, it will not be considered for use by owners, engineers, or contractors, regardless of its performance characteristics. Therefore, the focus of this research was to **develop mix designs for high performance concrete which combine desirable engineering properties (high strength, durability, low creep, etc.) with ease of use, placement, and reasonable cost**.

The research was conducted in two phases:

*1. **Material Identification Study** - Cement, Coarse Aggregate, and Fine Aggregate*
*2. **Mix Proportion Study***

Each phase of research was designed to systematically evaluate constituent materials and their properties. The material identification study was conducted by systematically isolating each material, and then characterizing its particular effect or suitability toward producing HPC. For example, the performance of several different cements was evaluated using reference mixes, in each case altering only the cement. Similarly, rock and then sand were evaluated based on their suitability to produce HS/HPC. Once suitable cements and aggregates were identified, attention was turned to developing mix designs for an ultra HSC (in excess of 14,000 psi) particularly suited to use in structural members that can exploit the high strength concrete (precast bridge girders, bridge piers). Although the research was conducted in the laboratory, placeability and workability were criteria considered in selecting appropriate materials and mixture designs.

CHAPTER 2

RESEARCH PROGRAM

2.1 Overview

Because of the natural variability of materials, high performance concrete (HPC) must be developed on a local level. Different cements, aggregates, and admixtures may yield concretes with different fresh and hardened properties.

This research was performed to identify local materials suitable for producing HPC and to evaluate the interaction of those constituent materials in HPC trial batches. To fulfill this objective, the research program was structured to systematically evaluate the constituent materials and isolate their effects on the properties of fresh and hardened HPC. The research plan was divided into the following tasks:

1. Establish properties of constituent materials
2. Material Identification: Cement Study
3. Material Identification: Aggregate Study
4. Mixture Proportion Study

In the first task, material properties were obtained for all relevant constituent materials. The type of information obtained included baseline properties of aggregates (specific gravity, gradings, fineness modulus, absorption, etc.) necessary to perform mixture proportion calculations, and properties of cements (fineness, chemical composition).

For the second task, the Cement Study, HPC mixtures were made holding all materials constant except the source/type of cement. Both fresh and hardened concrete properties were measured to establish how cements affect HPC performance.

In the Aggregate Study, all materials were held constant except the coarse or fine aggregate. Variations in fineness modulus were examined for fine aggregates, and different coarse aggregate source materials and gradings were tested in HPC mixtures. Fresh and hardened concrete properties were measured to determine the effects of aggregates on HPC.

Once the most promising constituent materials for HPC production were identified (Tasks 1 through 3), the Mixture Proportion Study was conducted. In this study, mixture proportions were varied to evaluate their effects on HPC performance. Variables examined included cementitious material content, water to cementitious material ratio (w/cm), and fly ash replacement.

In the following chapter, the methods and procedures used during the test program are outlined. First, procedures used to produce, cure, and test concrete specimens are described. The research tasks are then described in detail.

The experimental program was designed from a dual perspective. The primary focus of the program was to establish materials and mixture proportions conducive to producing *high strength* HPC. At the same time, effort was made to obtain a more general understanding of the effects of locally available materials, and their interactions, on the behavior of HPC.

2.2 Experimental Procedures

A summary of ASTM standards applicable to batching, curing, and testing concrete for the test program are presented in Table 2.1.

Table 2.1 ASTM Standards for Batching, Curing, and Testing

C 192	Making and Curing Concrete Test Specimens in the Laboratory
C 31	Making and Curing Concrete Test Specimens in the Field
C 511	Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C 566	Total Moisture Content of Aggregate by Drying
C 143	Slump of Hydraulic Cement Concrete
C 138	Unit Weight, Yield, and Air Content of Concrete
C 231	Air Content of Freshly Mixed Concrete by the Pressure Method
C 403	Time of Setting of Concrete Mixtures by Penetration Resistance
C 39	Compressive Strength of Cylindrical Concrete Specimens
C 469	Static Modulus of Elasticity of Concrete in Compression
C 496	Splitting Tensile Strength of Cylindrical Concrete Specimens
C 78	Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 157	Length Change of Hardened Hydraulic Cement Concrete

2.2.1 Correcting Batch Weights for Moisture

Regulating the water content of an HPC mixture is very important because of the low w/cm's typically used. Corrections to batch weights were made to compensate for moisture in the aggregates. Water contents of chemical admixtures were accounted for in the mixture designs. Concrete mixture proportions were determined using the absolute volume method.

A day or two before batching, coarse and fine aggregate of sufficient quantity were removed from stockpiles in the yard, turned over several times to ensure uniform moisture, and placed in 23 kg (50 lb) quantities into plastic buckets. Aggregate moisture contents were determined by oven drying representative samples. The buckets were fitted with lids to prevent aggregate moisture from escaping between the time of moisture sampling and time of batching.

2.2.2 Batching Concrete

Batching was carried out in a revolving drum, tilting mixer with a rated capacity of 0.17 m^3 (6 ft^3). About 0.10 m^3 (3.5 ft^3) of concrete was made for each batch.

Batching procedures complied with ASTM C 192, except for mixing duration. Because of its inherently low water content, HPC is less compromising than conventional concrete and requires a deliberate batching sequence and extended mixing time (Kojundic 1997). ASTM C 192 stipulates a three minute primary mixing interval after all materials are added, followed by a three minute rest period for taking initial slump, followed by a two minute final run. Initial slumps were frequently on the order of 25 mm (1 in.) or less. Therefore, an extended final mix of three to six minutes was used to effectively distribute the superplasticizer and thoroughly mix the dry HPC mixtures. The final mixing time was dictated by the nature of the mixture, batch size, and concrete temperature. Mixing continued until visual observation indicated all materials were well distributed and uniform consistency of the batch was reached.

During the mixture proportion study, which concentrated on mixtures with very low w/cm ratios using Type III cement, concrete consistency after the primary mixing interval was dry and clumpy. Therefore, initial slumps were not measured for these mixes.

The sequence for addition of materials to the mixer was the same for all batches. Coarse aggregate and about half of the mixing water was added to the mixer first. The remaining materials were combined gradually. Normal range water reducing or set retarding admixtures were introduced with the mixing water. High range water reducer (superplasticizer) was held back and added at the start of the final mixing period.

When work was done during summer and early autumn, the heat aggravated both workability and slump loss. Crushed ice was included in the mixing water to reduce the fresh concrete temperature to 5 to 10°C below ambient temperature, of which 35°C (95°F) was typical.

Specimen molds were lightly coated with oil. All specimens were consolidated by rodding. Plastic cylinder molds were filled and moved carefully to avoid skewing the specimen shape. All specimens were consolidated within 45 minutes of water being introduced to the mix.

2.2.3 Curing Concrete

Under standard curing, concrete cylinders, beams, and prisms were cured for the first 24 hours at 23 ± 1.7°C (73.4 ± 3°F) and 50 ± 4 percent relative humidity (RH). Occasionally, a number of cylinders were removed at 18 hours for compressive strength testing. The remaining molds were stripped at 24 hours. Cylinders and beams were then moist cured at 23 ± 1.7°C (73.4 ± 3°F) until the time of testing. Moist curing per ASTM C 192 was satisfied by immersion in lime-saturated water. After demolding, length change prisms were stored at 23 ± 1.7°C (73.4 ± 3°F) and 50 ± 4 percent RH to detect drying shrinkage.

2.2.4 Fresh Concrete Properties

Fresh concrete properties determined included initial and final slump, unit weight, air content, and concrete temperature. Initial concrete slump was measured after combining all materials but before addition of superplasticizer. Final concrete slump was measured after addition of superplasticizer and the final mixing period. Air content was measured by the pressure method.

2.2.5 Testing Concrete

Tests for compressive strength, modulus of elasticity, splitting tensile strength, modulus of rupture, and length change were scheduled at ages from 1 to 56 days. Usually, three specimens were tested for each age.

Compressive strength, modulus of elasticity, and modulus of rupture were determined using a 2,670 kN (600 kip) capacity testing machine. Splitting tensile strength tests were conducted in a 890 kN (200 kip) capacity testing machine.

Cylinders were tested for compressive strength and modulus of elasticity with reusable neoprene pads (85 durometer hardness). The pads were seated in steel or aluminum rings. Modulus of elasticity was determined with a compressometer jacket equipped with a linear variable differential transformer (LVDT).

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in.) plastic molds. It is recognized that size of the concrete cylinder influences compressive strength (Lessard et al. 1993). Several studies indicate that HPC compressive strength measured on 100 x 200 mm cylinders may exceed the strength measured on 150 x 300 mm (6 x 12 in.) cylinders by a factor of 1.01 to 1.05 .

Dimensions of modulus of rupture beams were 152 x 152 x 508 mm (6 x 6 x 20 in.). Length change prism dimensions were 76 x 76 x 286 mm (3 x 3 x 11.25 in.).

Compressive strength, modulus of elasticity, splitting tensile strength, and modulus of rupture specimens were tested in a moist condition as specified by ASTM C 192, C 39, C 496, and C 78. The moisture content of a concrete specimen substantially effects the resultant strength. A saturated specimen will reveal lower compressive strength and greater flexural strength than those for similar specimens tested dry (Kosmatka and Panarese 1994).

2.3 Establishing Material Properties

Analysis of constituent materials was completed prior to batching concrete. Analysis of concrete materials complied with the ASTM specifications listed in Table 2.2. Cement fineness and aggregate properties independently determined in this study correlated strongly with data available from manufacturers. Cement chemical compositions were provided by the cement manufacturers and were not independently verified.

Table 2.2 ASTM Standards for Concrete Materials

C 204	Fineness of Hydraulic Cement by Air Permeability Apparatus
C 702	Reducing Samples of Aggregate to Testing Size
C 33	Concrete Aggregates
C 136	Sieve Analysis of Fine and Coarse Aggregates
C 127	Specific Gravity and Absorption of Coarse Aggregate
C 128	Specific Gravity and Absorption of Fine Aggregate
C 29	Unit Weight and Voids in Aggregate

Cement fineness was determined using a Blaine air permeability apparatus. Cement fineness is a significant parameter influencing workability and early strength gain. Coarse and fine aggregate absorption, specific gravity, and grading, coarse aggregate void content and fine aggregate fineness modulus were determined. Aggregate properties are necessary for establishing mixture proportions and making adjustments for aggregate moisture.

2.4 Material Identification: Cement Study

This phase of the research centered on identification of local cements suitable for production of HPC. The test program included cements from a total of six cement plants in Oklahoma, Texas, Arkansas, and Kansas, and included four Type I's, two Type I/II's, one Type II, and one Type III. A list of the cements is presented in Table 2.3. Type I cements are classified for general purpose. Type II cements generate less heat of hydration. Type III cements are typically ground finer than Type I or II cements, leading to more rapid hydration and strength gain.

Table 2.3 Cements

Cement ID	Type	Manufacturer	Location
I.1	I	Lonestar	Pryor, OK
II.2	I/II	Lonestar	Pryor, OK
I.3	I	Ash Grove	Midlothian, TX
I.4	I	Ash Grove	Foreman, AR
II.5	I/II	Ash Grove	Chanute, KS
I.6	I	Holnam	Ada, OK
II.7	II	Holnam	Ada, OK
III.8	III	Holnam	Midlothian, TX

To study the effects of cement type and source on fresh and hardened concrete properties, each of the eight cements was used in two HPC mixture classes. These mixture classes were targeted to have 28 day compressive strengths in the ranges of 55 MPa (8,000 psi) and 69 MPa (10,000 psi). The mixtures were designated by the approximate cement content, and are referred to as the 7 sack mixture class and the 8.5 sack mixture class. Within each mixture class, all constituent materials and proportions were held constant, varying only the cement.

Table 2.4 contains the 7 sack and 8.5 sack proportions (saturated surface dry aggregates) for one cubic meter of concrete. The 7 sack mixture contained 385.5 kg/m^3 (650 lb/yd^3) cement and a w/cm of 0.41. The 8.5 sack mixture contained 462.6 kg/m^3 (780 lb/yd^3) cement and a w/cm of 0.35. Supplementary cementitious materials such as fly ash and silica fume were not included in this study so as to isolate the hydration activity of the cement.

Table 2.4 Mixture Proportions - Cement Study (per m^3)

	7 Sack Mixture	8.5 Sack Mixture
Cement, kg/m^3	385.5	462.6
Coarse Aggregate, kg/m^3	1,052.8	1,008.3
Fine Aggregate, kg/m^3	794.8	753.3
Mixing Water, kg/m^3	154.2	157.2
Set Retarder, L/m^3	0.77	0.89
Superplasticizer, L/m^3	3.02	4.18
w/cm	0.406	0.346
CA Content, %	64.4	61.7

1 kg/m^3 = 1.686 lb/yd^3 ; 1 fl.oz. = 29.6 mL ; 1 fl.oz/yd^3 = 38.7 mL/m^3

Crushed limestone coarse aggregate was used for both mixture designs. The crushing process eliminates potential zones of weakness within the aggregate. Limestone absorption and specific gravity measured 1.2 percent and 2.67, respectively. The 7 sack mixture contained aggregate meeting the No. 67 grading requirements of ASTM C 33. Nominal maximum size of No. 67 aggregate is 19 mm (3/4 in.). The 8.5 sack mixture aggregate met a No. 8 gradation with a nominal maximum size of 10 mm (3/8 in.). Surface area of smaller size aggregate allows better bond with cement paste.

Coarse aggregate to fine aggregate weight ratio was maintained at about 1.3. The coarse aggregate content, determined as a fraction of the dry rodded unit weight (DRUW), calculated to 65 percent for the 7 sack mixture and 62 percent for the 8.5 sack mixture. Both mixtures contained natural Oklahoma river sand with a fineness modulus of 2.5, absorption of 0.7 percent, and specific gravity of 2.63.

Concrete mixtures in this study contained a normal range water reducer/retarder, W.R. Grace Daratard 17 (ASTM C 494 Type D), and a superplasticizer, W.R. Grace Daracem 19 (ASTM C 494 Type F). Water reducing admixtures are necessary for adequate slump at very low w/cm ratios. By temporarily relaxing the natural attraction between cement grains and water, they act as a powerful dispersing agent. This action permits more cement particles to ultimately react with water. The addition rate of normal range water reducer/retarder for both mixes was about 200 mL/100 kg cement (3.1 fl.oz/100 lb cement). The 7 sack mixture contained 780 mL/100 kg cement (12.0 fl.oz/100 lb cement) of superplasticizer. The 8.5 sack mixture, with a lower w/cm ratio, contained 900 mL/100 kg cement (13.8 fl.oz/100 lb cement) of superplasticizer.

One batch of each mixture was tested in the first round. Mixtures were then repeated between three and five times for comparison. Cement II.7 was dropped from the study after the first round of batching when it was no longer available from the manufacturer. Modulus of rupture testing was also discontinued after the first round of batching.

Compressive strength measurements were performed at 1, 3, 7, 28, and 56 days. Modulus of elasticity, splitting tensile strength, and modulus of rupture tests were conducted at 28 days.

2.5 Material Identification: Aggregate Study

In this phase of the research, local coarse and fine aggregates were examined for their suitability in producing HPC. Most of the study focused on coarse aggregates, although some tests were conducted to examine fine aggregate grading. It was believed that an increase of the fine aggregate coarseness could afford a decrease in the w/cm ratio for a given workability. The fineness modulus, a number describing the fine aggregate grading, was increased by blending limestone screenings with the river sand.

As shown in Table 2.5, four crushed aggregates were included in the Coarse Aggregate test program. These aggregates are all available in Oklahoma. The coarse aggregates included limestone and rhyolite from south-central Oklahoma, granite from southwestern Oklahoma, and a weathered sandstone river gravel from southeastern Oklahoma. Some uncrushed particles were observed in the river gravel.

Each of the coarse aggregates was tested in concrete mixtures in two conditions: 1) a standard grading, and 2) the commercial (as received) grading. The standard grading was selected to meet the No. 7 grading requirements of ASTM C 33. Individual size fractions were separated and weighed in the quantity required for each batch. This approach allowed independent examination of the grading and aggregate type.

Table 2.5 Coarse and Fine Aggregates

Aggregate	As received nominal MSA	Location	Supplier
Limestone	3/4 in.	Davis, OK	Dolese Co.
Limestone	3/8 in. chips	Davis, OK	Dolese Co.
Granite	5/8 in.	Snyder, OK	Meridian Aggregates
Rhyolite	5/8 in.	Davis, OK	Western Rock
Weathered Sandstone River Gravel	5/8 in.	Broken Bow, OK	B&B Sand and Gravel
River Sand	(Fineness modulus of 2.5)	Dover, OK	Dolese Co.
Limestone Washed Shot	(Fineness modulus of 4.7)	Davis, OK	Dolese Co.

1 in. = 25.4 mm

The concrete mixture used for all batches was designed to have sufficient strength to promote contrast between the coarse aggregates. The mix contained 474.5 kg/m^3 (800 lb/yd^3) Type I cement and 166.1 kg/m^3 (280 lb/yd^3) Class C fly ash. The mixture was designed with a w/cm of 0.28 and a constant coarse aggregate content of 63 percent of the DRUW.

Two batches were made for each mixture combination. Compressive strength and length change measurements were performed at 1, 3, 7, 28, and 56 days. Modulus of elasticity testing, which included plot of the stress/strain loop, was performed at 7 and 28 days. Splitting tensile strength and modulus of rupture testing was conducted at 28 days.

2.6 Mixture Proportion Study

Selected materials were used to determine mixture proportions for consistently producing concrete with adequate workability and compressive strength. Trial batching proceeded with a matrix encompassing the effects of cementitious material content, water to cementitious material (w/cm) ratio, and fly ash replacement. This batching matrix is presented in Table 2.6.

Table 2.6 Batching Matrix for Mixture Proportion Study

Total Cementitious Material (kg/m^3)	Cement Only			Fly Ash Replacement of 10 percent		Fly Ash Replacement of 20 percent	
	w/cm 0.32	w/cm 0.30	w/cm 0.28	w/cm 0.30	w/cm 0.28	w/cm 0.28	w/cm 0.26
400	X	X				X	
450	X					X	
475		X					
500	X	X	X	X	X	X	X
550		X	X	X	X	X	X
600		X	X			X	X
650		X	X				
700		X					
750		X					

The same materials were used for each mixture. All concrete mixtures contained Holnam/Midlothian Type III cement, No. 8 limestone aggregate, natural sand with a fineness modulus of 2.5, and W.R. Grace admixtures WRDA with Hycol and Daracem 19. Compressive strength cylinders were standard cured at 23°C and 50 percent RH for the first 24 hrs, then moist cured at 23°C.

CHAPTER 3

EXPERIMENTAL RESULTS

3.1 Overview

The findings of the *Material Identification Study* and the *Mixture Proportion Study* are contained in this chapter. The Material Identification Study was undertaken to identify locally available cements, fine aggregates, and coarse aggregates as to their suitability for use in high strength HPC. Each of these constituent materials was varied, in turn, in HPC mixtures and their effects on fresh and hardened concrete properties observed. Once suitable constituent materials were identified, focus shifted to determining the effects caused by changing the proportions of the materials in HPC mixtures, executed in the Mixture Proportion Study.

Results of the Material Identification Study are presented first. Effects of changing the cement source and type are presented, followed by observations gained from changing fine aggregate gradation. Next, results obtained from changing the coarse aggregate type and gradation are presented.

Results of the Mixture Proportion Study occupy the remainder of the chapter. These include findings related to: 1) cementitious material content, 2) supplementary cementitious materials (use of Class C fly ash), and 3) water to cementitious material ratio.

To reiterate from Chapter 2, the experimental program was designed and the results analyzed from a dual perspective. The dominant focus of the research was on producing *high strength* HPC. At the same time, the goal of gaining a more general understanding of the effects of locally available materials, and their interactions, on the behavior of HPC was continually addressed.

3.2 Material Identification Study

3.2.1 Changing Cement Source and Type

In the cement study, concretes with two different water-cement ratios (w/c) were tested, varying only the cement source for a given w/c. Thus, the effects of cement type and source on the properties of HPC were studied at two compressive strength levels. Eight different cements were tested, including Types I, II, and III, from a total of six sources (cement plants). The lower strength mixture contained approximately 7 sacks of cement per cu. yd. (387 kg/m^3; 650 lb/cyd) and the higher strength mixture contained about 8.5 sacks of cement per cu. yd. (464 kg/m^3; 780 lb/cyd). At each strength level, all other parameters were held constant, i.e., proportions, type of coarse and fine aggregate, and type and dosage of chemical admixtures. Chemical admixtures included a conventional water reducing and retarding admixture (ASTM C 494 Type D) coupled with a high range water reducing admixture (HRWR)(ASTM C 494 Type F). Mineral admixtures were not included in these mixtures. All specimens were wet cured at 23 ± 1.7°C (73.4 ± 3°F).

Proportions (saturated surface dry condition) for the 7 sack and 8.5 sack mixtures are shown in Table 3.1. The w/c's for the mixtures were 0.40 and 0.34, respectively. For the lower strength mixture, the coarse aggregate met an AASHTO #67 gradation, with a nominal maximum particle size of 19 mm (3/4 in.). The higher strength mixture contained coarse aggregate with a 9.5 mm (3/8 in.) maximum particle size. Both of the limestone aggregates came from the same quarry in central Oklahoma. The same fine aggregate, a river sand, was used for all batches at both strength levels. The conventional water reducer/retarder was a hydroxylated organic compound, and possessed slight air entraining capabilities. The HRWR was a modified naphthalene sulfonate. Chemical admixture dosage rates used for the two mixture classes are contained in Table 3.1.

Cement samples from production facilities in Oklahoma, southern Kansas, western Arkansas, and northern Texas were represented in the eight cement test group. Compound compositions of the cements, as provided by the suppliers, are shown in Table 3.2. Cements are designated by Type (I, II, or III) followed by an identification number (.1 through .8).

The values of Blaine fineness presented in the Table 3.2 were independently determined using an air permeability apparatus in accordance with ASTM C 204. These values agreed well with the values of fineness provided by the cement suppliers. For the most part, chemical compositions for the cements were similar to one another, with the exceptions of lower C_3A contents for the Type II cements, and higher fineness and lower C_2S for the Type III cement.

Plastic concrete properties and set times for the sixteen mixes are shown in Table 3.3. For the 7 sack mixtures, initial slumps (obtained before addition of the HRWR) were between 32-115 mm (1-1/4 and 4-1/2 in.), with most falling in the 38-57 mm range (1-1/2 to 2-1/4 in.). Initial slumps for the 8.5 sack mixes were generally on the order of 13 mm (½ in.) because of the lower w/c ratio. After addition of the HRWR, slumps were in excess of 230 mm (9 in.) for all mixtures. Measured air contents were similar for all mixtures, ranging from 1.3 to 3.0 percent, with most mixes having air contents of around 2.0 to 2.5 percent. These values are consistent with commonly accepted values for entrapped air. No air entraining admixtures were used. Measured unit weights ranged from 2360 kg/m^3 to 2445 kg/m^3 (147.4 lb/ft^3 to 152.6 lb/ft^3). The average unit weight for the 7 sack mixes was slightly higher than for the 8.5 sack mixes, 2416 kg/m^3 vs. 2400 kg/m^3 (150.9 lb/ft^3 vs. 149.9 lb/ft^3).

Table 3.1 Mixture Proportions (per m^3) for Cement Study

	7 Sack Mixtures	8.5 Sack Mixtures
Water (kg)	154	157
Cement (kg)	387	464
Coarse Aggregate (kg)	1,053[a]	1,009[b]
Fine Aggregate (kg)[c]	795	753
Conventional WR (mL)	773	889
HRWR (mL)	3,017	4,177
w/c	0.40	0.34
Sand Fraction of Total Aggregate by Wt.	0.43	0.43
HRWR Dosage (mL/kg cement)	7.81	9.02

Notes: a. #67 crushed limestone, max. particle size = 19 mm
b. "3/8 in. chips" crushed limestone, max. particle size = 9.5 mm
c. "Dover Sand," Fineness Modulus=2.50

1 kg/m^3 = 1.686 lb/yd^3; 1 fl.oz. = 29.6 mL ; 1 fl.oz/yd^3 = 38.7 mL/m^3, 1 in.= 25.4 mm

Table 3.2 Compound Composition (percent) and Fineness of Cements

	Designation							
	I.1	**I.3**	**I.4**	**I.6**	**II.2**	**II.5**	**II.7**	**III.8**
C_3S	56.5	54.4	54.1	58	57.6	54	56	57.1
C_2S	16.9	18.4	18.5	18	17.4	21	22	13.8
C_3A	10.8	11.4	12.4	9	5.2	8	4	10.5
C_4AF	7.2	-	8.6	8	13.3	10	12	-
Blaine Fineness (cm^2/gm)	3510	3390	3600	3690	3480	3610	3600	5490

- data not available

Table 3.3 Properties of Plastic Concrete - Cement Study

	Mixture	Initial Slump (mm)	Final Slump (mm)	Air Content (%)	Unit Weight (kg/m³)	Initial Set (hr)	Final Set (hr)
		ASTM C143		ASTM C231	ASTM C138	ASTM C403	
7 Sack Mixtures	I.1-7	114	>230	2.3	2360	8.9	9.7
	I.3-7	44	>230	2.7	2430	11.2	12.3
	I.4-7	38	>230	2.0	2435	11.8	13.2
	I.6-7	38	>230	2.0	2425	-	-
	II.2-7	57	>230	1.6	2420	9.9	10.5
	II.5-7	32	>230	2.0	2425	11.0	12.0
	II.7-7	57	>230	2.0	2445	17.5	19.0
	III.8-7	32	>230	2.5	2385	6.8	7.7
8.5 Sack Mixtures	I.1-8.5	6	>230	2.2	2395	11.5	12.9
	I.3-8.5	6	>230	2.3	2415	11.5	13.6
	I.4-8.5	13	>230	3.0	2395	18.2	19.2
	I.6-8.5	25	>230	2.0	2405	10.6	11.5
	II.2-8.5	13	>230	1.6	2380	30.0	31.7
	II.5-8.5	6	>230	2.0	2405	-	-
	II.7-8.5	13	>230	1.3	2420	19.3	20.7
	III.8-8.5	6	>230	2.0	2385	8.3	9.2

1 in. = 25.4 mm, 1 kg/m³ = 0.0624 lb/ft³   - data not available

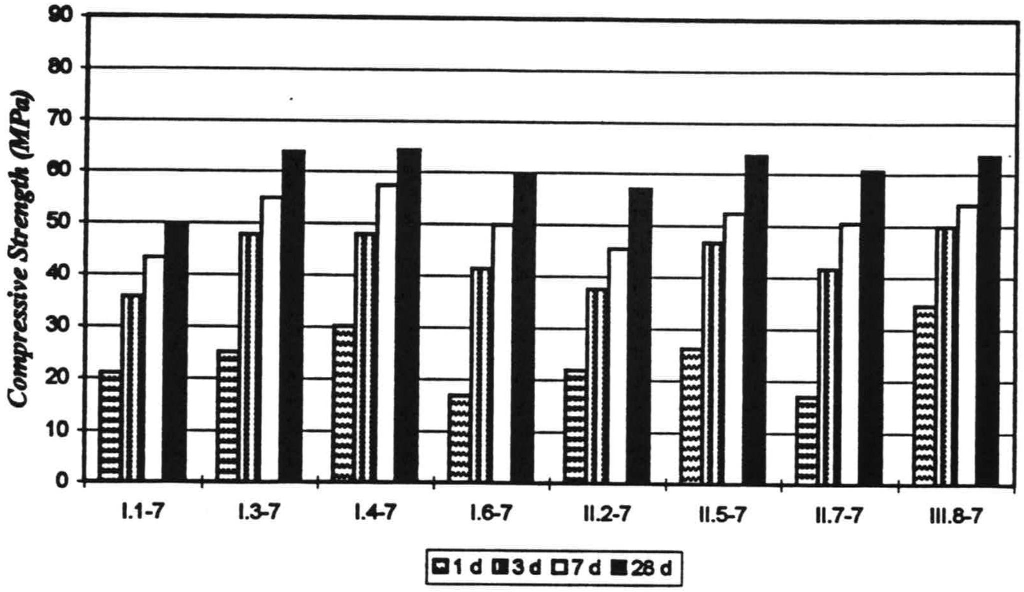
While slumps, unit weights, and air contents were somewhat similar for all the mixes, variations were observed in time to initial and final set. Time to set was measured on concrete mixtures with all material larger than a #4 sieve removed (ASTM C403), rather than on mortar mixtures. On average, for both the 7 sack and 8.5 sack mixtures, the concrete made with Type II cements required the longest set times, followed by the Type I cements. Batches containing the Type III cement had the shortest setting times as expected. For the Type I cements, initial sets were generally in the range of about 9 to12 hrs. The Type III cement's initial set was considerably shorter than that of the Type I cements, by about 2 to 4 hrs. Also, on average, set times for the 8.5 sack mixtures were about 2 hrs longer than for the 7 sack mixtures, with the exception of cement II.2 (about 20 hrs longer). It is inconclusive as to whether cement II.2 was incompatible with the HRWR at the increased dosage rate used for the 8.5 sack mix. The time from initial set to final set ranged from about 0.5 to 2 hrs for all mixes.

Measured compressive strengths at 1, 3, 7, and 28 d are contained in Figs. 3.1 and 3.2. Each reported strength represents the average strength of three, 100 x 200 mm (4 x 8 in.) cylinders. Overall the average 28 day strength of the 7 sack concrete was 60.2 MPa (8,740 psi) with an average standard deviation of 5.13 MPa (744 psi). For the 8.5 sack concrete mixtures, the average 28 day strength was 71.7 MPa (10,410 psi) with average standard deviation of 4.73 MPa (686 psi).

In Fig. 3.1 (7 sack mixtures), the 28 day strengths for all eight mixtures are very near the average value of 60.2 MPa (8,740 psi) except for mixture I.1-7, which possessed a 28 d strength of 49.3 MPa (7,150 psi), about 18 percent less than the average of the other 7 sack mixtures. Concrete mixture I.4-7 achieved the highest 28 d strength of 64.3 MPa (9,330 psi), which is only 7 percent greater than the average of all 7 sack concretes tested.

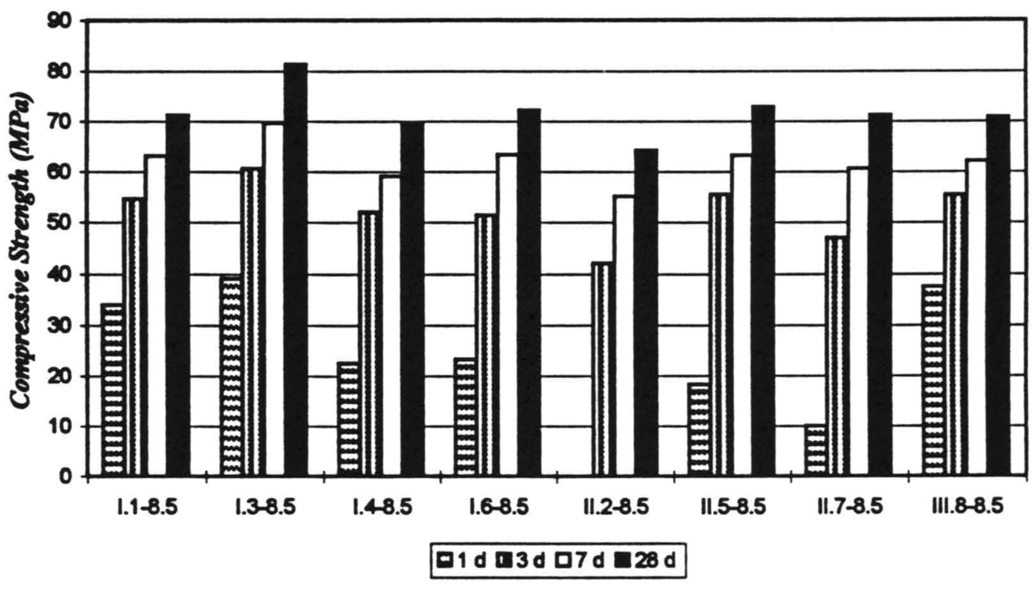
Figure 3.2 depicts the concrete strengths of the 8.5 sack mixtures for all ages. From these charts, it is apparent that the highest 28 d strength was achieved by mixture I.3-8.5. Its 28 d strength was 81.4 MPa (11,810 psi) which is about 13 percent greater than the average 28 day strength for these eight mixtures. Of the remaining seven mixtures, only one 28 d strength fell below 68.9 MPa (10,000 psi); an average 28 day strength of 64.2 MPa (9,320 psi) was measured for mixture II.2-8.5.

Figures 3.1 and 3.2 also illustrate the differences in strength gain with age. In general, the concrete made with Type III cement gained strength more rapidly (due to the cement's greater fineness) than concretes made with the Type I and II cements. Comparing the 7 sack concretes, the Type III concrete made 34.5 MPa (5,010 psi) at 1 day, whereas the Type I concretes achieved an average of 23.2 MPa (3,370 psi) and the Type II concrete achieved an average of 21.6 MPa (3,140 psi) at one day. Comparing the 8.5 sack mixtures, the concrete made with Type III cement achieved a 1 day



1 ksi = 6.89 MPa

Figure 3.1 Strength Gain for 7 Sack Mixtures



1 ksi = 6.89 MPa

Figure 3.2 Strength Gain for 8.5 Sack Mixtures strength of 37.4 MPa (5,430 psi), whereas the concretes made with Type I cement averaged a 1 day strength of 29.6 MPa (4,300 psi).

Although the rapid strength gain achieved by using Type III cement is apparent from the data, the Type II cements do not appear to substantially delay strength gain when compared to Type I cements. This is discovered by examining the strength gain with age for the different mixtures of concrete, and evidenced by the overlapping concrete strengths from the Type I and Type II cements, especially at early ages. This indicates that very few real differences exist between these Type I cements and Type II cements. The exception to this observation is for 1 d compressive strengths of the 8.5 sack concretes made with Type II cements (Fig. 3.2). Mixture II.7-8.5 achieved lower 1 d strengths than the other cements, and mixture II.2-8.5 did not have sufficient strength to be tested at 1 day. From Table 3.2 that lists cement chemical compositions and finenesses, the fineness of the Type II cements is essentially the same as the Type I cements. The fineness of the Type II cements average 3545 cm^2/g whereas the Type I cements have an average fineness of 3550 cm^2/g. The Type II cements are distinguished only by reduced amounts of C_3A which should result in reduced heat of hydration.

Overall, the variations in 28 day concrete strengths between the different cements appear to be slight, and the concrete strengths tend to group tightly around the average for each class of concrete. To compare the effects of cement on concrete strengths, 90 percent confidence intervals were computed for the 28 day strengths of each mixture. A confidence interval is a statistical measure that rates the probability that the true average strength for the population (for a given mixture) will fall within a specified range. For the 7 sack mixtures, these comparisons indicated that some measurable differences in concrete strength can be attributable to the cement used to make the concrete. For example, the concretes from mixture I.1-7 and mixture II.2-7 fell measurably below the average value for strengths in this mix class. No statistical difference was found to exist between the 28 day strengths for mixtures I.3-7, I.4-7, II.5-7, II.7-7 and III.8-7.

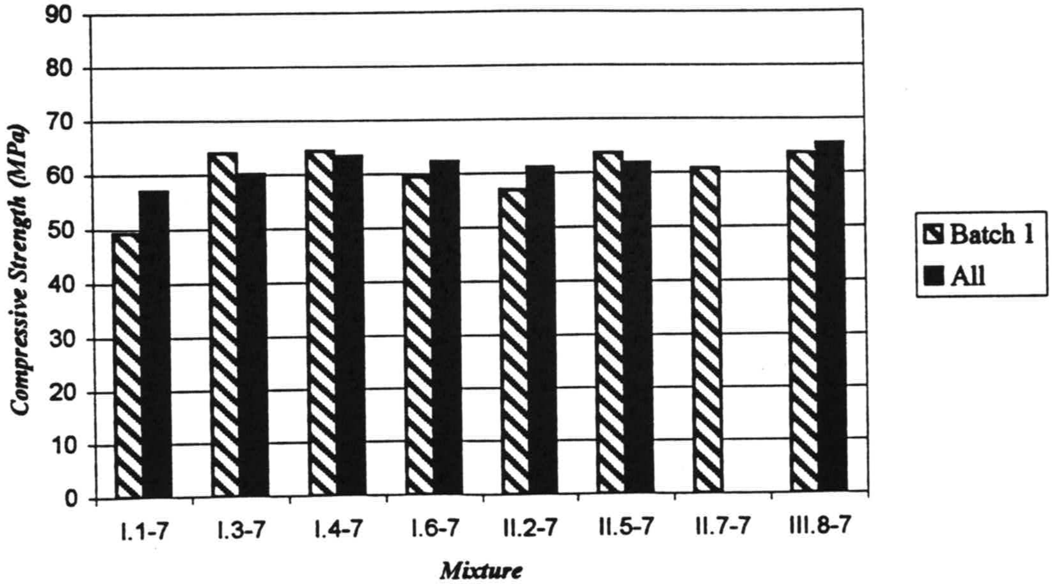
Ninety percent confidence intervals for concretes from the 8.5 sack mix class were also computed. Only one mixture (II.2-8.5), possessed 28 day strengths significantly less than the average of the other mixtures. Conversely, the cement used in mixture I.3-8.5 could hold high potential for the manufacture of high-strength concrete. Taken as a whole, comparisons indicate that one cement, designated I.3, could be more suitable than the other cements for the production of high-strength concrete.

In reviewing the data, questions could be raised as to whether the observed differences in concrete strength result from variations in cement source, or rather the differences were produced by naturally occurring variations in the data. To address this concern, three separate casts were made using the same cement source and the same mixture proportions. The concrete strengths from these three casts were then compared at 1, 7, and 28 days. From these three casts, the average 28 d strength varied no more than 3.5 percent and the 90 percent confidence limits were overlapping, indicating that nearly identical concrete strengths were produced when the same cement was used. As an extension, the consistency demonstrated by these three casts indicates the variations in strength observed between concretes made with different cements were likely caused by the variations in cement, as all other constituent materials and procedures were held constant.

Additional data was also generated approximately one year after the first round of batches. Cement samples were again obtained from the same suppliers, with the exception that cement II.7 was no longer available. For each cement at each strength level, two additional batches were cast and compressive strengths measured. Compressive strengths at 28 d age are shown for the 7 sack and 8.5 sack mixtures in Figs. 3.3 and 3.4, respectively. The plots contain results from the first batch (Figs. 3.1 and 3.2), and the average of all three batches. For a given cement and mixture, compressive strengths of the two latter batches were generally in close agreement with one another. However, some differences were observed when compared to the results of the first set of batches. The overall trends remained similar to those observed from the first set of batches in that, for the most part, the strengths were fairly close to the average for all mixtures. This exercise highlighted the fact that not only may there be differences between cements, but also that characteristics of a given cement may change over time due to variations in production and raw materials used in the manufacturing process.

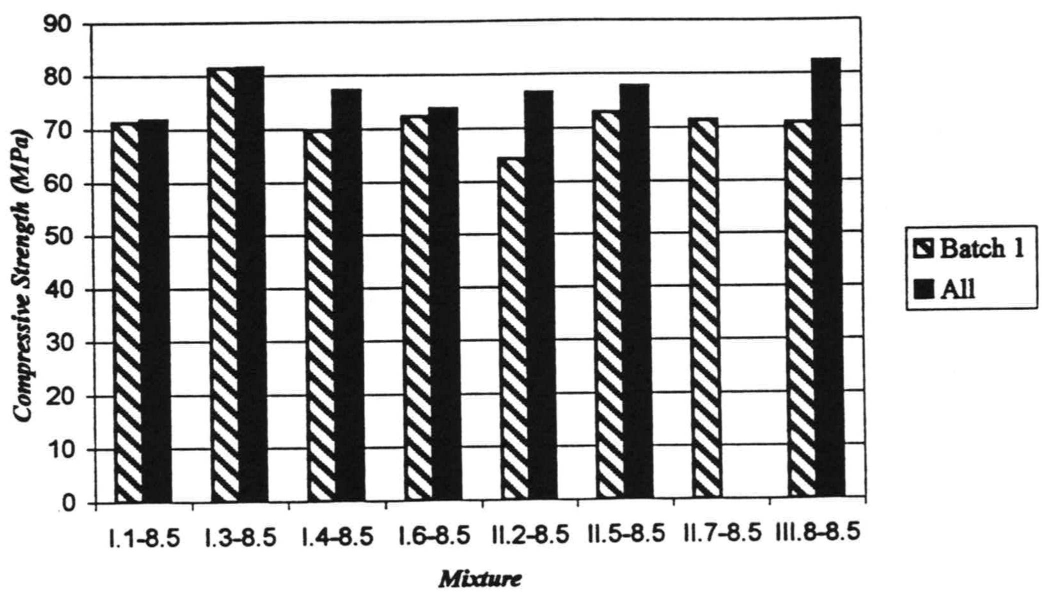
The modulus of elasticity at 28 d is reported for each mixture in Table 3.4. Elastic modulus was determined using a compressometer in accordance with ASTM C 469. The average from two cylinders was used for each modulus data point reported.

For the 7 sack mixture class, the modulus of elasticity averaged 41.3 GPa (5,990 ksi) for all casts with a standard deviation of 1.69 GPa (245 ksi), or 4.1 percent. For the higher strength concrete, the modulus of elasticity averaged 40.9 GPa (5,930) ksi with standard deviation of 1.80 GPa (261 ksi), or 4.4 percent. Interestingly, the average modulus of elasticity was slightly lower for higher strength (8.5 sack) concretes, 40.9 GPa vs. 41.3 GPa. This observation is contrary to the accepted equations for elastic modulus that relate E_c as a function of concrete strength. In Fig. 3.5, the measured values for E_c are illustrated in a plot vs. the values for E_c that would be predicted from the equations, $E_c = 3{,}320\sqrt{f'_c} + 6900\ MPa$ $(40{,}000\sqrt{f'_c} + 1.0 \times 10^6\ psi)$ recommended by ACI Committee 363 for high strength concrete (ACI 1992), and the AASHTO (1992) equation, $E_c = 4{,}730\sqrt{f'_c}\ MPa$ $(57{,}000\sqrt{f'_c}\ psi)$. The figure clearly depicts that no strong trend can be established that relates the elastic modulus



1 ksi = 6.89 MPa

Figure 3.3 28 d Compressive Strengths for 7 Sack Mixtures



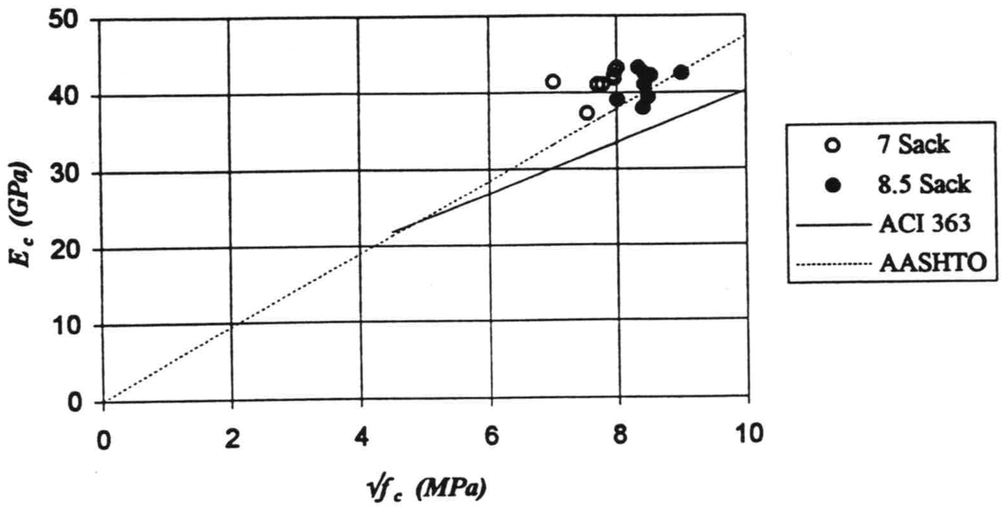
1 ksi = 6.89 MPa

Figure 3.4 28 d Compressive Strengths for 8.5 Sack Mixtures

Table 3.4 28 d Elastic Moduli, Modulus of Rupture, and Splitting Tensile Strength - Cement Study

	Mixture	Measured E_c (GPa)	Measured Modulus of Rupture (MPa)	Measured Splitting Tensile Strength (MPa)
7 Sack Mixtures	I.1-7	41.4	4.90	3.55
	I.3-7	42.8	6.31	4.48
	I.4-7	43.1	6.62	4.55
	I.6-7	41.0	6.41	4.21
	II.2-7	37.2	5.48	4.31
	II.5-7	42.1	6.83	4.48
	II.7-7	41.0	5.76	4.52
	III.8-7	41.7	6.79	4.21
	AVERAGE (STD. DEV.)	41.3 (1.69)	6.14 (0.65)	4.29 (0.31)
8.5 Sack Mixtures	I.1-8.5	41.0	8.07	5.10
	I.3-8.5	42.4	7.48	4.65
	I.4-8.5	43.1	7.72	4.96
	I.6-8.5	39.3	7.83	3.96
	II.2-8.5	39.0	6.69	4.96
	II.5-8.5	42.1	7.52	4.41
	II.7-8.5	42.4	8.00	4.76
	III.8-8.5	37.9	7.38	5.24
	AVERAGE (STD. DEV.)	40.9 (1.80)	7.58 (0.41)	4.76 (0.39)

1 ksi = 6.89 MPa



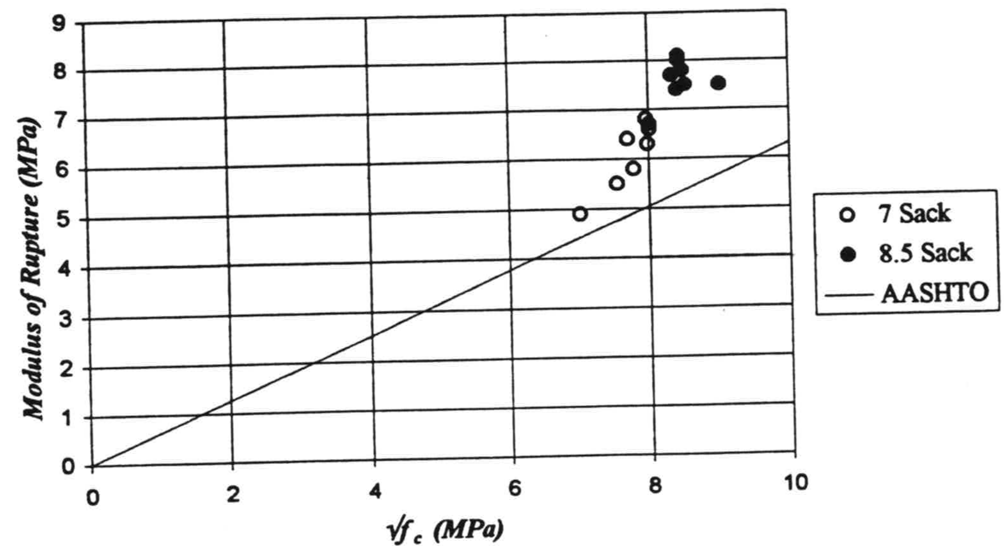
1 ksi = 6.89 MPa

Figure 3.5 Modulus of Elasticity vs $\sqrt{f'_c}$ - Cement Study

to concrete strength. Instead, both classes of concrete, the 7 sack mixture and the 8.5 sack mixture, possessed roughly equivalent elastic moduli. This is possibly a reflection that the same coarse aggregate (crushed limestone) was used in roughly the same amounts for both mixture classes, even though the 7 sack mixture class used a larger aggregate than the 8.5 sack mixtures, 19 mm vs. 9.5 mm.

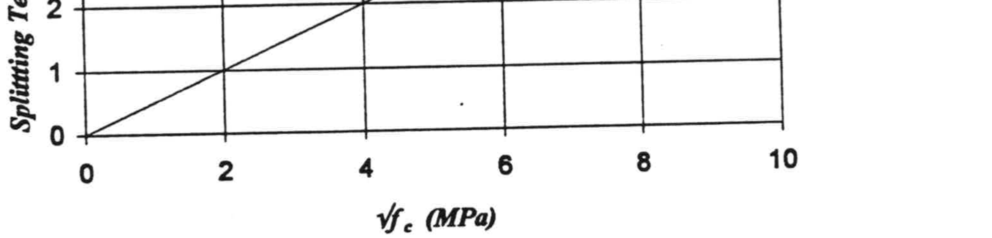
On the other hand, higher compressive strengths tended to result in higher tensile strengths. For the lower strength 7 sack concretes, the average modulus of rupture (MOR) at 28 d was 6.1 MPa (890 psi) whereas the higher strength 8.5 sack concretes produced an average MOR of 7.58 MPa (1,100 psi). This trend is evidenced by the data presented in Fig. 3.6, which illustrates a dramatic increase in MOR with corresponding increases in compressive strength. In Fig. 3.6, the AASHTO MOR is given by $0.63\sqrt{f'_c}\,MPa$ $(7.5\sqrt{f'_c}\,psi)$.

The data also indicate that the 28 d splitting tensile strength increases with compressive strength. These results are illustrated in Fig. 3.7, where the predicted tensile strength is given by $0.50\sqrt{f'_c}\,MPa$ $(6\sqrt{f'_c}\,psi)$.



1 ksi = 6.89 MPa

Figure 3.6 Modulus of Rupture vs $\sqrt{f'_c}$ - Cement Study



1 ksi = 6.89 MPa

Figure 3.7 Splitting Tensile Strength vs $\sqrt{f'_c}$ - Cement Study

3.2.2 Changing Fine and Coarse Aggregate

3.2.2.1 Fine Aggregate Study. Fine aggregate gradation impacts water demand of fresh concrete. Mixtures with coarser sands generally require less water to achieve a given fresh concrete workability. Therefore, the effect of using fine aggregate with a higher fineness modulus was studied to see if total mixing water could be reduced, leading to a lower w/cm ratio.

Companion mixtures were cast using identical mixture proportions, changing only the fineness modulus, to determine if the variation in FM would impact compressive strength. The desired fineness modulus was achieved by blending a crushed limestone "washed shot" product with the river sand. The washed shot material was a by-product of coarse aggregate crushing, and consisted of clean crushed limestone particles of more or less uniform 1/8 in. size.

Mixture proportions for the batches of the Fine Aggregate Study are shown in Table 3.5. Mixtures FM1, FM2, FM3 and FM4 were sets of companion batches in which only the fineness modulus was varied (from 2.5 to 3.3). Mixtures FM1 and FM2 contained fly ash and had w/cm of

Table 3.5 Mixture Proportions (per m^3) for Fine Aggregate Study

	FM1	FM2	FM3	FM4
Water (kg)	177	177	154	154
Cement (kg)	474	474	386	386
Class C Fly Ash (kg)	166	166	-	-
Coarse Aggregate (kg)	1,040	1,040	1,053	1,053
Sand (kg)	526	337	795	510
Washed Shot (kg)	-	189	-	285
Total Fine Aggregate (kg)	526	526	795	795
Fineness Modulus	2.5	3.3	2.5	3.3
Sand Fraction of Tot. Agg. (by wt.)	0.34	0.34	0.43	0.43
w/cm	0.28	0.28	0.40	0.40
Conventional WR (mL)	947	947	592	592
HRWR (mL)	2,250	2,250	1,924	1,924
Measured Slump (mm)	140	150	175	195
28 d Compressive Strength (MPa)	84.7	88.4	65.0	61.8

1 kg/m^3 = 1.686 lb/yd^3 ; 1 fl.oz. = 29.6 mL ; 1 $fl.oz/yd^3$ = 38.7 mL/m^3, 1 in.= 25.4 mm

0.28. Mixtures FM3 and FM4 had no fly ash and used a w/cm of 0.40. Pairs of mixtures (FM1 and FM2, and FM3 and FM4) were batched back to back on the same day to minimize the effects of ambient conditions on fresh concrete properties. All compressive strength cylinders were wet cured at standard temperature.

Compressive strengths at 28 d for the mixtures are also shown in Table 3.5. It is apparent that no clear trend exists regarding the effect of changing the fineness modulus on compressive strength, within the ranges examined. Comparison of average compressive strengths of mixtures FM1 vs FM2, and FM3 vs FM4 indicates no clear change in strength due to increasing the fineness modulus from 2.5 to 3.3. Also, little actual change in slump was observed from increasing the fineness modulus from 2.5 to 3.3 (Table 3.5). Therefore, the fineness modulus of fine aggregate was not investigated further.

3.2.2.2 Coarse Aggregate Study. Four sources of coarse aggregate were tested in HPC mixtures to determine their suitability for producing high-strength HPC. The aggregates included crushed *limestone* from central Oklahoma, crushed *rhyolite* from central Oklahoma, crushed *granite* from southwestern Oklahoma, and weathered sandstone *river gravel* (predominantly crushed, but with some uncrushed larger particles) from southeastern Oklahoma. Each coarse aggregate was used in mixtures in two conditions: 1) a "standard" grading, and 2) the commercial (as-received) grading. The standard grading was selected to fall within the specifications for AASHTO #7 material. Use of the standard grading isolated differences in strength due to the coarse aggregate materials themselves, such as mineralogy, surface texture, and particle shape. Mixtures containing coarse aggregate with the commercial grading were compared to the companion mixtures with standard grading to examine potential strength differences related to the grading.

Measured properties of the aggregates and their gradings are shown in Tables 3.6 and 3.7, respectively. Particle size distributions are also shown in Fig. 3.8. The commercial limestone was finer than the other three coarse aggregates (Table 3.7, Fig. 3.8), and had a maximum particle size of approximately 9.5 mm (3/8 in.). The rhyolite, granite, and gravel had maximum size particles of 15.9 mm (5/8 in.). To achieve the standard grading, each coarse aggregate was separated into different sizes and recombined in the required amounts. The commercial 9.5 mm (3/8 in.) limestone material was augmented with larger material from the same quarry to achieve the standard grading.

All mixtures (both commercial and standard gradings) in the coarse aggregate study used the proportions shown in Table 3.8. The mixtures had a constant *volume of DRUW aggregate per unit concrete volume* equal to 0.64, and were proportioned by absolute volume. Since each aggregate had a slightly different bulk specific gravity, minor differences in absolute coarse and fine aggregate

Table 3.6 Properties of Coarse Aggregates

Property	Limestone LI	Rhyolite RH	Granite GN	River Gravel GV
Bulk Specific Gravity (SSD)	2.67	2.71	2.62	2.59
Percent Absorption (SSD)	1.2	1.4	0.5	1.3
DRUW, Standard (kg/m³)	1590	1510	1520	1605
DRUW, Commercial (kg/m³)	1620	1520	1500	1630

DRUW = Dry Rodded Unit Weight; 1 lb/ft³ = 16.02 kg/m³

Table 3.7 Coarse Aggregate Gradings (Percent Passing)

Sieve Size	Commercial Grading				Standard Grading
	Limestone LI	Rhyolite RH	Granite GN	Gravel GV	All
19.05 mm (3/4 in.)	100	100	100	100	100
12.5 mm (½ in.)	100	91.5	92.6	91.2	91
9.5 mm (3/8 in.)	94.2	62.4	48.5	67.5	59
4.75 mm (#4)	16.4	8.7	0.9	11.2	2
2.36 mm (#8)	4.7	2.7	0.4	1.9	0

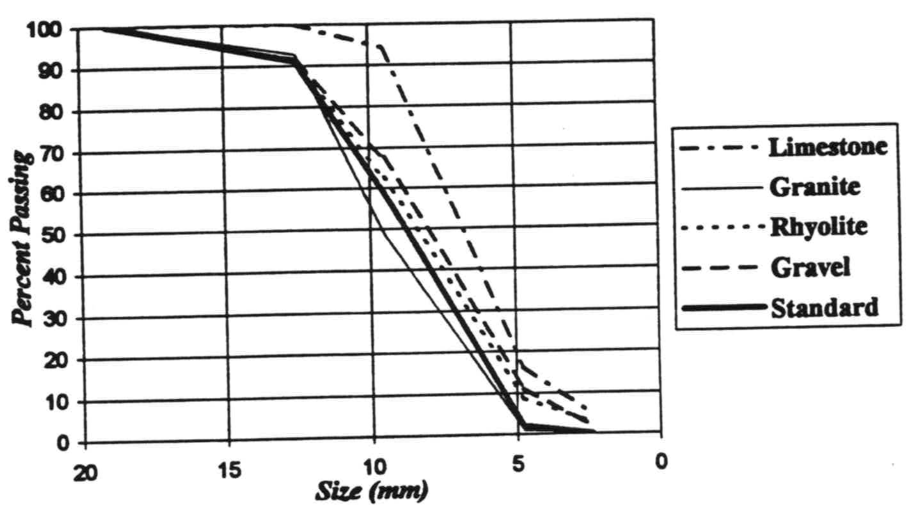


Figure 3.8 Coarse Aggregate Gradings

Table 3.8 Mixture Proportions (per m^3) for Coarse Aggregate Study

Water (kg)	177
Cement (kg)	474
Fly ash (kg)	166
w/cm	0.28
Conventional Water Reducer (mL) (ASTM C 494 Type A)	1255
High Range Water Reducer (mL) (ASTM C 494 Type F)	2925
Fine Aggregate (kg)	496-617
Coarse Aggregate (kg)	957-1040
Coarse Aggregate Content, Dry Rodded Volume per Concrete Volume	0.64

1 kg/m^3 = 1.686 lb/yd^3 ; 1 fl.oz. = 29.6 mL ; 1 fl.oz/yd^3 = 38.7 mL/m^3

weights were required to achieve the constant ratio of 0.64. The mixtures all contained 25 percent fly ash and had w/cm of 0.28. Sixteen (16) mixtures were batched, two for each coarse aggregate material (limestone, rhyolite, granite, gravel) in each grading condition (commercial, standard). Compressive strengths at 1, 3, 7, and 28 days were determined, and modulus of elasticity was measured at 7 and 28 days. All specimens were wet cured at 23 ± 1.7°C (73.4 ± 3°F).

Measured compressive strengths at 1, 7, and 28 days are shown in Table 3.9. Compressive strengths at 28d are also shown in Fig. 3.9. Average results from six 100 x 200 mm (4 x 8 in.) cylinders (three per batch) were used for each data point reported. Designations in the table and figure indicate the aggregate type (LI=limestone, RH=rhyolite, GN=granite, GV=gravel) and grading (s=standard, c=commercial). Compressive strengths at 28 days ranged from 64.8 to 85.2 MPa (9,410 to 12,360 psi).

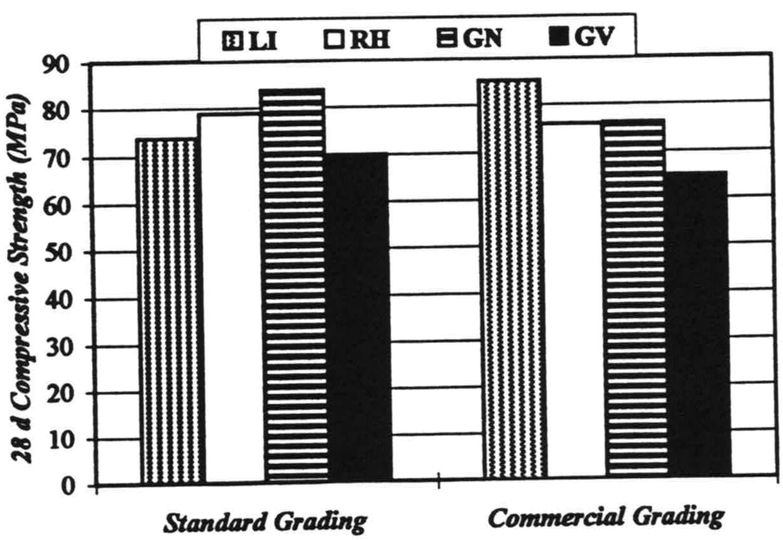
Ninety-five percent confidence intervals were computed for 28 day strengths of all mixtures. When comparing average strengths for mixtures, if the 95 percent confidence intervals did not overlap, the resulting strengths were considered to be significantly different, i.e., not due to chance.

For the standard grading (same grading for all aggregate types), strengths of mixtures ranged from 70.0 MPa (10,160 psi) to 83.7 MPa (12,150 psi) at 28 days. The average compressive strength was 76.5 MPa (11,090 psi) and the average standard deviation was 1.45 MPa (210 psi). Confidence

Table 3.9 Compressive Strengths, Coarse Aggregate Study

	Standard Grading					Commercial Grading				
	LIs	**RHs**	**GNs**	**GVs**	**Ave**	**LIc**	**RHc**	**GNc**	**GVc**	**Ave**
1 d Strength (MPa)	23.3	25.3	30.2	24.6	25.8	26.9	28.8	23.6	22.1	25.4
7 d Strength (MPa)	59.7	64.2	69.0	56.6	62.4	69.9	62.6	61.9	51.7	61.6
28 d Strength (MPa)	73.7	78.8	83.7	70.0	76.5	85.2	75.9	76.1	64.8	75.5

1 ksi = 6.89 MPa



1 ksi = 6.89 MPa

Figure 3.9 28 d Compressive Strengths, Coarse Aggregate Study intervals for the 28 day strengths of these mixtures did not overlap indicating significant quantifiable differences can be attributed to the coarse aggregate. The highest strength was observed for the mixtures containing granite (9 percent above the average), followed by rhyolite, limestone, and gravel. The limestone aggregate produced strengths slightly below the average, while the gravel resulted in strengths about 9 percent lower than the average. The lower strength of the mixtures with river gravel is consistent with the reduced bond associated with the smooth particle surfaces. The granite, rhyolite, and limestone have rougher textures, possibly leading to higher strengths. Granite and rhyolite, being dense, hard aggregates, produced the highest strength mixtures for the standard grading.

Mixtures with the commercial (as-received) grading yielded 28 day compressive strengths ranging from 64.8 MPa to 85.2 MPa (9,410 psi to 12,360 psi). The average 28 day strength was 75.5 MPa (10,960 psi) with an average standard deviation of 2.00 MPa (290 psi). As with the standard grading, strengths of the river gravel mixtures were found to be lower than for mixtures containing the other aggregates. Granite and rhyolite mixtures had the same (statistically similar) intermediate strength of 76 MPa. However, unlike for the standard grading, the mixtures with limestone produced the highest strength. The dramatically increased strength of the limestone mixtures (nearly 16 percent as compared to the standard grading) is likely due to the smaller aggregate size in its commercial grading. Smaller coarse aggregate particles tend to produce less microcracking in the transition zone, leading to improved strength. The commercial limestone was a nominal 9.5 mm (3/8 in.) maximum size material, while the other three aggregates were nominal 15.9 mm (5/8 in.) in size.

With regard to compressive strength, it is evident that the limestone, rhyolite, and granite aggregates are all suitable for production of HPC with strengths in excess of 69 MPa (10,000 psi). The granite and rhyolite appear to hold better potential for producing mixtures of even higher strengths, especially if gradings utilize smaller average particle sizes (such as 9.5 mm, similar to the commercial limestone). The limestone produced mixtures with laboratory strengths in excess of 85 MPa (12,300 psi) when used in the smaller (9.5 mm) maximum particle size, but achieved lower (10,700 psi) strengths when used at the standard grading. The results show that river gravel can be used to produce HPC, although lower compressive strengths than the other aggregates should be expected.

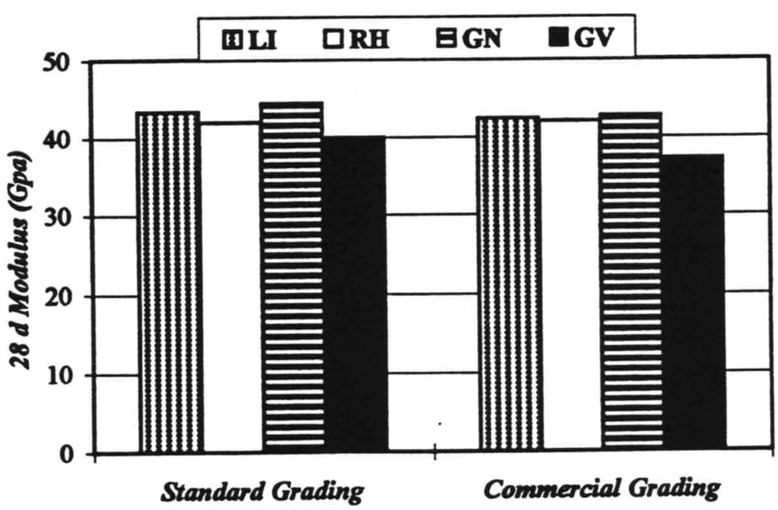
Elastic moduli at 7 and 28 days are shown for the mixtures in Table 3.10; 28 d moduli are also shown in the bar chart of Fig. 3.10. Modulus of elasticity (ASTM C 469) was obtained by averaging the results from four 100 x 200 mm (4 x 8 in.) cylinders. Measured values ranged from a low of 37.2 GPa to a high of 44.4 GPa (5,800 to 6,450 ksi). At 28 days, granite produced the highest modulus (44.4 GPa) for the standard grading; however, large differences in modulus were not observed between mixtures containing limestone, rhyolite, or granite at a given age and for a given grading. Mixtures containing river gravel had moduli substantially lower than for the other aggregates (ranging from 34.8 to 40.0 GPa), for both commercial and standard gradings, at 7 and 28 days.

Unlike in the cement study, moduli generally increased from age 7 days to age 28 days, slightly more so for the mixtures with the standard aggregate grading. Increases were on the order of

Table 3.10 Modulus of Elasticity, Coarse Aggregate Study

	Standard Grading					Commercial Grading				
	LIs	RHs	GNs	GVs	Ave	LIc	RHc	GNc	GVc	Ave
7 d E_c (GPa)	40.0	41.7	40.3	36.5	39.6	40.7	42.4	41.0	34.8	39.7
28 d E_c(GPa)	43.4	42.0	44.4	40.0	42.5	42.4	42.0	42.7	37.2	41.1

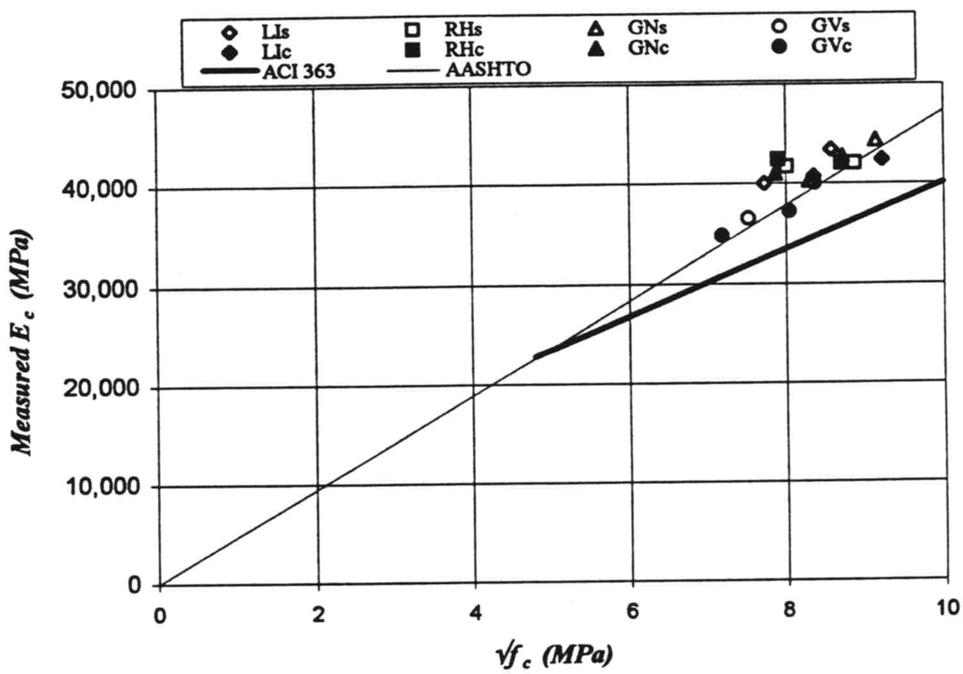
1 ksi = 6.89 MPa



1 ksi = 0.00689 GPa

Figure 3.10 28 d Elastic Moduli, Coarse Aggregate Study

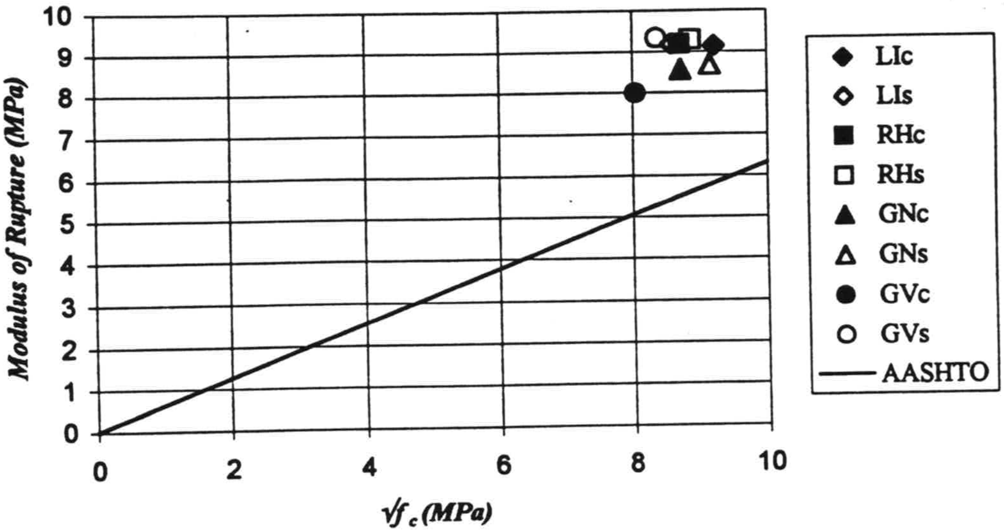
4 to 7 percent for mixtures with commercial gradings and about 10 percent for mixtures with the standard grading. Mixtures with rhyolite aggregate exhibited essentially the same modulus (42.0 GPa (6,100 ksi)) for both gradings and ages. The general trend of increase in modulus with age can be seen in Fig. 3.11. The solid lines indicate modulus predicted from the equation, $E_c = 3,320\sqrt{f'_c} + 6900$ *MPa* ($40,000\sqrt{f'_c} + 1.0 \times 10^6$ *psi*), recommended for high-strength concrete (ACI 363 1992) and the AASHTO (1992) equation, $E_c = 4,730\sqrt{f'_c}$ *MPa* ($57,000\sqrt{f'_c}$*psi*). The ACI Committee 363 equation for modulus of high strength concrete was conservative for the mixtures tested.



1 ksi = 6.89 MPa

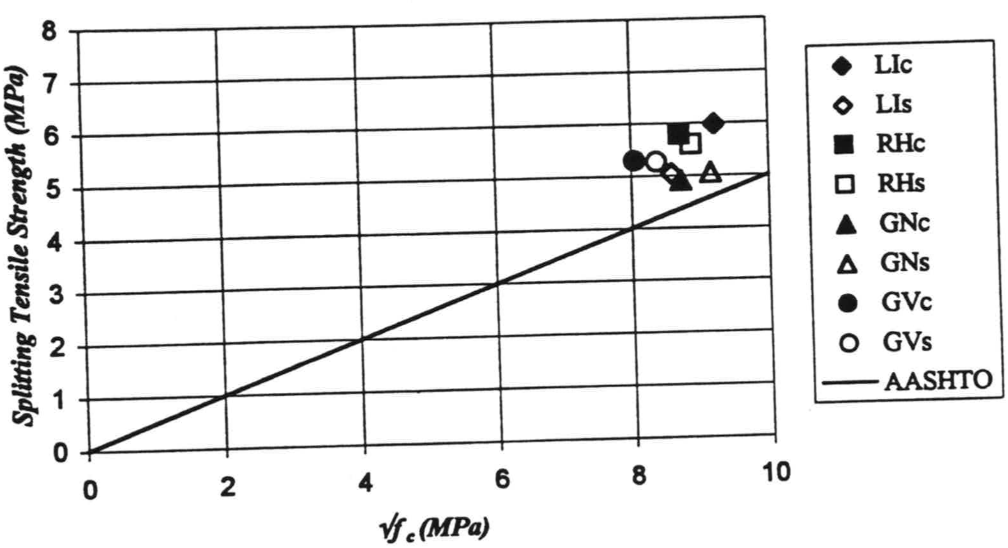
Figure 3.11 Modulus of Elasticity vs $\sqrt{f'_c}$ - Coarse Aggregate Study

Modulus of rupture and splitting tensile strength are plotted in Figs. 3.12 and 3.13, respectively. The coarse aggregate type and grading (within the range tested) had no clear effect on the modulus of rupture or splitting tensile strength. As can be seen in the figures, the AASHTO equations $0.63\sqrt{f'_c}$ *MPa* ($7.5\sqrt{f'_c}$ *psi*) and $0.50\sqrt{f'_c}$ *MPa* ($6\sqrt{f'_c}$ *psi*) were conservative in predicting these parameters.



1 ksi = 6.89 MPa

Figure 3.12 Modulus of Rupture vs √f'$_c$ - Coarse Aggregate Study



1 ksi = 6.89 MPa

Figure 3.13 Splitting Tensile Strength vs √f'$_c$ - Coarse Aggregate Study

3.3 Mixture Proportion Study

The mixture proportion study followed earlier testing phases which identified specific constituent materials that are suitable for the manufacture of HPC. Cements, coarse aggregates, fine aggregates and to a lesser extent, admixtures had all been identified through the materials identification studies. The mixture proportion study built on the earlier findings and focused primarily on the proportioning of the various ingredients to produce workable and placeable concrete mixtures with outstanding strength characteristics. Certainly, hardened concrete properties other than strength can qualify concrete as HPC. However, this research study emphasized the production of concrete suitable for use in pretensioned concrete bridge girders, so the strength characteristics in the hardened state were emphasized. Mixture designations for the mixtures tested are shown in Table 3.11.

Table 3.11 Mixture Designations

Total Cementitious Material (kg/m³)	Cement Only			Fly Ash Replacement of 10 percent		Fly Ash Replacement of 20 percent	
	w/cm 0.32	w/cm 0.30	w/cm 0.28	w/cm 0.30	w/cm 0.28	w/cm 0.28	w/cm 0.26
400	37	8				25	
450	38(A,B)	7(A,B)				26	
475		9(B,C,D)					
500	39	6(A,B)	18	33	34(A,B)	27(B,C,D,E)	32
550		5	14	35	36	28B	31
600		4	15			29	30
650		3	16				
700		2					
750		1					

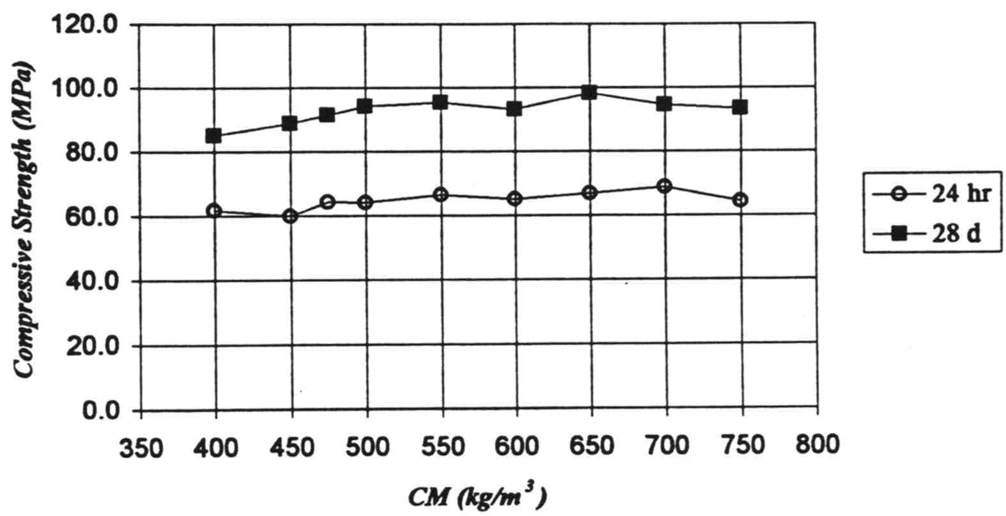
1 kg/m³ = 1.686 lb/yd³

3.3.1 Cementitious Material Content

Thirteen (13) concrete mixtures were batched where the water to cementitious material ratio (w/cm) was held constant at 0.30. In each batch, Type III cement was used as the only cementitious material (fly ash was not employed in these batches). The total cement content varied from 400 kg/m³ to 750 kg/m³ (674 to 1265 lb/cyd). The purpose of the test series was to determine the cement content required to optimize strength (with due consideration given to workability). The w/cm of 0.30 was chosen as a representative w/cm based on testing performed in the material identification study.

Fresh concrete properties were measured at the time of batching and included concrete temperature, ambient temperature, ambient relative humidity, and unit weight. Concrete compressive strengths were measured at 18 hr, 24 hr, and 28 days. Mixture proportions, fresh concrete properties and concrete strengths are reported in Table 3.12. Mixtures are listed in the table in order of decreasing cement content.

The data indicate that the maximum 28 day compressive strength of 98.2 MPa (14,240 psi) was achieved with Mixture #3. However in general, the 28 day compressive strengths maximized at 93 to 95 MPa (13,500 to 13,800 psi) with cementitious contents that equaled or exceeded 500 kg/m^3 (843 lb/cyd). As cementitious contents exceeded 500 kg/m^3, little or no improvement in concrete strengths were noted. The data is plotted in Figure 3.14. As can be seen from this plot, concrete strengths do not improve with additional cement beyond 500 kg/m^3. Furthermore, both the figure and the plot indicate that the compressive strengths at 1 day also leveled out at the cementitious materials content of 500 kg/m^3 and did not appreciably exceed 67 MPa (9700 psi).



1 ksi = 6.89 MPa

Figure 3.14 Effect of CM on Compressive Strength

Table 3.12 Properties of Mixtures with w/cm=0.30

Mix No		1	2	3	4	5	6A	6B	9B	9C	9D	7A	7B	8
Cement	*kg/m³*	*750*	*700*	*650*	*600*	*550*	*500*	*500*	*475*	*475*	*475*	*450*	*450*	*400*
Coarse Agg	kg/m³	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1	1062.1
Fine Agg	kg/m³	300.0	383.5	464.2	547.5	629.4	711.4	711.4	751.7	751.7	751.7	793.4	793.4	875.3
Water	kg/m³	218.0	203.0	189.0	174.0	159.5	145.0	145.0	138.0	138.0	138.0	130.5	130.5	116.0
WR	L/m³	2.25	2.10	1.95	1.80	1.65	1.50	1.50	1.43	1.43	1.43	1.36	1.35	1.20
HRWR	L/m³	9.75	9.10	8.45	7.80	7.15	6.50	6.50	6.18	6.18	6.18	5.85	5.85	5.20
Conc. Temp.	°C	21.1	27.8	30.0	36.7	29.4	28.3	13.3	28.9	28.1	22.2		20.8	27.5
Ambient Temp.	°C	32.8	38.3	35.6	37.8	38.9	36.7		37.2	28.3	32.2	30.6	32.2	37.8
RH	%	63	46	50	45	35	36		48	50	55	90	49	47
Final Slump	mm			260		200	190	100	0	0	170	150	100	20
Unit Wt.	kg/m³		2387		2414	2410	2414	2423	2415	2428	2447	2407	2441	2426
18hr fc	MPa	63.0	65.1	62.9	62.8	61.7	63.5		62.6	60.7		55.8		55.7
1 d fc	MPa	64.3	68.7	66.8	65.0	66.4	67.5	60.4	37.2	68.4	57.4	62.5	57.5	61.6
28 d fc	MPa	93.3	94.5	98.2	93.0	95.3	94.9	93.1	91.9	93.2	88.7	89.1	88.5	85.0

1 ksi = 6.98 MPa; 1 kg/m³ = 1.686 lb/yd³; 1 fl.oz. = 29.6 mL ; 1 fl.oz/yd³ = 38.7 mL/m³, 1 in.= 25.4 mm

3.3.2 Supplementary Cementitious Material

Type C fly ash was incorporated into the mixture proportion study as a supplementary cementitious material. Experimental testing was performed to provide direct comparisons with regard to the effects of fly ash as a cementitious supplement. Primarily, fly ash affects two important concrete properties: compressive strength at early ages and workability. The following generalized statements can be made regarding the effect of fly ash on concrete:

- Concretes made with fly ash are more workable, often indicated by increased slump for a given w/cm ratio;
- Concretes made with fly ash possess lower strength at one day of age than concretes made without fly ash (same w/cm), and;
- Concretes made with fly ash exhibit essentially identical strength at 28 days of age as concretes made without fly ash (same w/cm).

These statements are supported by the data reported in Table 3.13. The table reports slumps and compressive strengths at one day and 28 days for concrete mixtures with w/cm ratios of 0.30, 0.28 and 0.26. Cementitious materials contents were held constant at either 500 kg/m^3 or 550 kg/m^3. At a cementitious materials content of 500 kg/m^3 and a w/cm ratio of 0.28, note that the slump increases from 20 mm (0.75 in.) with no fly ash to 110 mm (4.25 in.) slump with 10 percent fly ash and finally to 180 mm (7 in.) slump with 20 percent fly ash. As the workability increases with increased fly ash content, the compressive strength at 28 days remains fairly constant, ranging between 94.3 and 98.2 MPa (13,700 and 14,200 psi). However, the compressive strength at one day decreases with increased fly ash content. One day strength is 66.7 MPa (9670 psi) without fly ash but only 50.3 MPa (7,300 psi) with 20 percent replacement. The same trends are noted for concrete mixtures made with a total cementitious content of 550 kg/m^3.

However, the improved workability of fly ash can also directly benefit the strength of the concrete. With improved workability comes the opportunity to reduce w/cm ratios and effectively increase compressive strength. This conclusion is supported with the data from concrete mixtures made with a w/cm ratio of 0.26. The lower w/cm is possible because fly ash is used as a replacement for cement. The measured slumps of concretes made with 20 percent fly ash and a w/cm of 0.26 are approximately the same as the slumps of concrete made without fly ash, but at a w/cm of 0.28. Notably, 28 day compressive strengths improve with decreases in w/cm to 0.26. Therefore, it is possible to produce higher strength concrete by using fly ash as a replacement for cement, largely because lower w/cm ratios are possible.

Table 3.13 Effects of Fly Ash on Slump and Compressive Strength

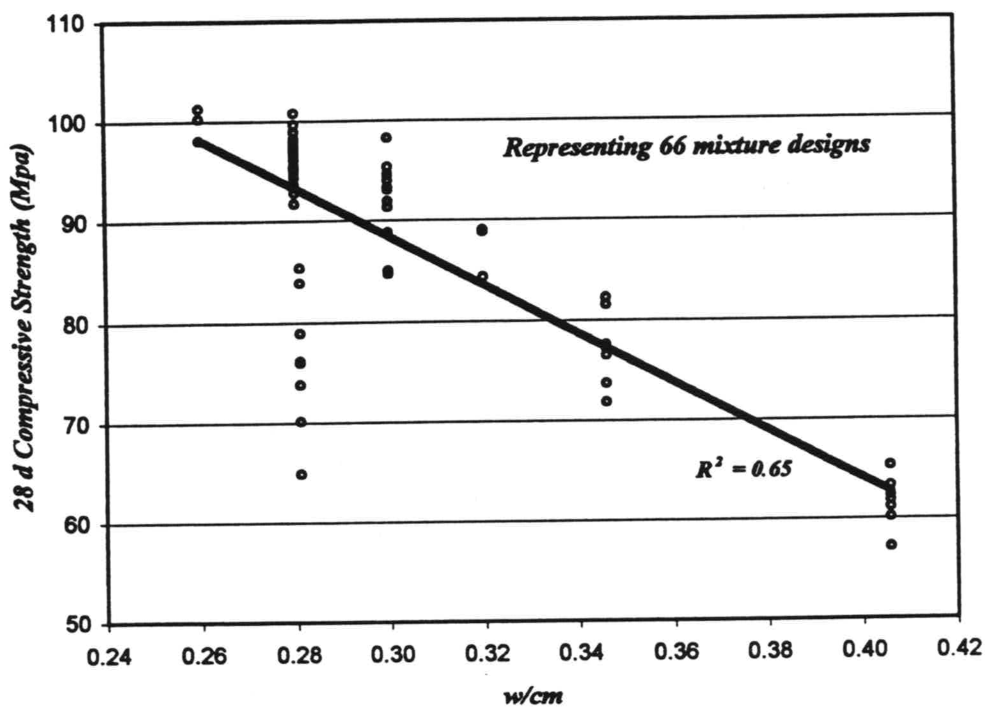
Total Cementitious Material (kg/m^3)	Cement Only		Fly Ash Replacement of 10 percent		Fly Ash Replacement of 20 percent	
	w/cm 0.30	w/cm 0.28	w/cm 0.30	w/cm 0.28	w/cm 0.28	w/cm 0.26
	Slump (mm)					
500	140	20	210	110	180	10
550	200	110	220	100	220	120
	1 d Compressive Strength (MPa)					
500	64.0	66.7	51.9	58.9	50.3	55.5
550	66.4	67.7	52.9	60.2	49.2	55.1
	28 d Compressive Strength (MPa)					
500	94.0	98.2	91.9	96.0	94.3	100.2
550	95.3	95.5	94.6	99.6	97.2	98.0

1 kg/m^3 = 1.686 lb/yd^3; 1 ksi = 6.98 MPa; 1 in. = 25.4 mm

3.3.3 Water to Cementitious Materials Ratio

Through testing to date, 66 concrete mixtures have been batched and tested for compressive strength at 28 days. Many of these 66 mixtures have been batched more than once. The data have been compiled and plotted in Fig. 3.15. The figure plots the average 28 day compressive strength for concrete made with a given mixture design vs. the w/cm ratio. The results clearly show that w/cm ratio is a direct indicator for concrete strength. Linear regression indicates that as w/cm ratio increases, compressive strengths decrease.

Additionally, the plot indicates that if workable concrete mixtures with w/cm ratios less than 0.28 can be attained, then compressive strengths can increase beyond the current levels tested. The statistical correlation between w/cm ratio and 28 day compressive strength is a moderately strong 0.65, indicating that while direct correlation does exist, other factors are also affecting compressive strengths. However, it is important to point out that this plot includes all data from our testing program. Included within these data are concretes made with different cements, different fly ash replacement ratios, different coarse aggregates, and sands with varying fineness moduli. Also, a variety of admixtures have been employed for various reasons. All in all, considering the wide range of materials and admixtures that have been tested, the moderately strong correlation between strength and w/cm is remarkable.



1 ksi = 6.89 MPa

Figure 3.15 Variation in Compressive Strength with w/cm

CHAPTER 4

CONCLUSIONS

1. Excellent sources of high quality cements, fine aggregates, and coarse aggregates are available in Oklahoma to produce high strength HPC with compressive strengths in the range of at least 100 MPa (14,500 psi). In various portions of the study, 28 d strengths as high as 100.7 MPa (14,600 psi) and 56 d strengths up to 109.5 MPa (15,900 psi) were attained.
2. Test data indicate that while compressive strengths from mixtures using cements from different sources were generally closely grouped, cement source and type can affect compressive strengths of concrete. Therefore, engineers, constructors and transportation agencies should be aware of the possible differences in performance of HS/HPC when using different cements.
3. Modulus of elasticity was largely unaffected by changing the source and/or type of cement.
4. Variation in fineness modulus of fine aggregate from 2.5 to 3.3 had no clear effect on concrete compressive strength, and only a minor effect on workability. Therefore, fineness modulus in this range is not a significant factor affecting performance of HPC.
5. For the coarse aggregate study, when using a standard grading, granite aggregate produced mixtures with higher compressive strengths than rhyolite and limestone, though all three exceeded 73.7 MPa (10,700 psi) at 28 d; mixtures with river gravel achieved strengths substantially lower than for the other aggregates. The river gravel does not appear well suited to producing concrete with 28 d strengths in excess of about 70 MPa.
6. Limestone aggregate with the commercial grading achieved the highest compressive strength of all mixtures tested in the coarse aggregate study (85.2 MPa (12,350 psi)). This result is believed to be closely tied to reduced microcracking in the transition zone due to the smaller particle sizes of the commercial limestone aggregate.
7. Granite aggregate produced mixtures with slightly higher modulus of elasticity than the limestone and rhyolite aggregates. River gravel mixtures produced moduli substantially lower than the average for all aggregates. A modest increase in modulus was observed from 7 to 28 days for all mixtures containing aggregates except rhyolite, which remained unchanged.
8. Overall, the expression $E_c = 3,320\sqrt{f'_c} + 6900$ *MPa* ($40,000\sqrt{f'_c} + 1,000,000$ *psi*), developed for HPC, underestimated the elastic modulus by 10 to 20 percent for both the cement study and the coarse aggregate study.

9. Prediction equations for modulus of rupture, $0.63\sqrt{f'_c}\,MPa$ $(7.5\sqrt{f'_c}\,psi)$, and splitting tensile strength, $0.50\sqrt{f'_c}\,MPa$ $(6\sqrt{f'_c}\,psi)$, were conservative for both the cement and coarse aggregate studies.

10. Increases in total cementitious material content above approximately 500 kg/m^3 (843 lb/cyd) resulted in little gain in compressive strength at 1 and 28 days age.

11. Replacement of up to 20 percent of the portland cement with Class C fly ash reduced early compressive strengths, but improved workability and allowed use of a lower w/cm which effectively increased long term compressive strength.

REFERENCES

AASHTO (1992). Standard Specification for Highway Bridges, 15th edition, Washington, D.C.

ACI Committee 363 (1983). *State-of-the-Art Report on High-Strength Concrete ACI 363R-92*, American Concrete Institute, Detroit, Michigan, 55 pp.

Aïtcin, P., and Neville, A. (1993). "High-Performance Concrete Demystified," *Concrete International*, V 15, No 1, January, pp. 21-25.

American Society for Testing and Materials (1995a). Air Content of Freshly Mixed Concrete by the Pressure Method (C 231), V. 4.02, Philadelphia, 1995, pp. 134-141.

American Society for Testing and Materials (1995b). Compressive Strength of Cylindrical Concrete Specimens (C 39), V. 4.02, Philadelphia, 1995, pp. 17-21.

American Society for Testing and Materials (1995c). Concrete Aggregates (C 33), V. 4.02, Philadelphia, 1995, pp. 10-16.

American Society for Testing and Materials (1995d). Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (C 78), V. 4.02, Philadelphia, 1995, pp. 31-33.

American Society for Testing and Materials (1995e). Fineness of Hydraulic Cement by Air Permeability Apparatus (C 204), V. 4.01, Philadelphia, pp. 161-169.

American Society for Testing and Materials (1995f). Length Change of Hardened Hydraulic Cement Concrete (C 157), V. 4.02, Philadelphia, 1995, pp. 101-106.

American Society for Testing and Materials (1995g). Making and Curing Concrete Test Specimens in the Field (C 31), V. 4.02, Philadelphia, pp. 5-9.

American Society for Testing and Materials (1995h). Making and Curing Concrete Test Specimens in the Laboratory (C 192), V. 4.02, Philadelphia, pp. 116-122.

American Society for Testing and Materials (1995i). Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes (C 511), V. 4.02, Philadelphia, pp. 270-271.

American Society for Testing and Materials (1995j). Reducing Samples of Aggregate to Testing Size (C 702), V. 4.02, Philadelphia, 1995, pp. 361-364.

American Society for Testing and Materials (1995k). Sieve Analysis of Fine and Coarse Aggregates (C 136), V. 4.02, Philadelphia, 1995, pp. 78-82.

American Society for Testing and Materials (1995l). Slump of Hydraulic Cement Concrete (C 143), V. 4.02, Philadelphia, 1995, pp. 88-90.

American Society for Testing and Materials (1995m). Specific Gravity and Absorption of Coarse Aggregate (C 127), V. 4.02, Philadelphia, 1995, pp. 64-68.

American Society for Testing and Materials (1995n). Specific Gravity and Absorption of Fine Aggregate (C 128), V. 4.02, Philadelphia, 1995, pp. 69-73.

American Society for Testing and Materials (1995o). Splitting Tensile Strength of Cylindrical Concrete Specimens (C 496), V. 4.02, Philadelphia, 1995, pp. 266-269.

American Society for Testing and Materials (1995p). Static Modulus of Elasticity of Concrete in Compression (C 469), V. 4.02, Philadelphia, 1995, pp. 241-244.

American Society for Testing and Materials (1995q). Time of Setting of Concrete Mixtures by Penetration Resistance (C 403), V. 4.02, Philadelphia, 1995, pp. 217-221.

American Society for Testing and Materials (1995r). Total Moisture Content of Aggregate by Drying (C 566), V. 4.02, Philadelphia, 1995, pp. 282-283.

American Society for Testing and Materials (1995s). Unit Weight and Voids in Aggregate (C 29), V. 4.02, Philadelphia, 1995, pp. 1-4.

American Society for Testing and Materials (1995t). Unit Weight, Yield, and Air Content of Concrete (C 138), V. 4.02, Philadelphia, 1995, pp. 83-85.

Caldarone, M., Gruber, K., and Burg, R. (1994). "High-Reactivity Metakaolin: A New Generation Mineral Admixture," *Concrete International*, V 16, No 11, November, pp. 37-40.

Carrasquillo, P. and Carrasquillo, R. (1986). "Guidelines for the Use of High Strength Concrete in Texas Highways," Research Report 367-1F, Center for Transportation Research, The University of Texas at Austin, Austin, TX, August.

Chicago Committee on High-Rise Buildings (1977). *High Strength Concrete in Chicago High-Rise Buildings*, Task Force Report No. 5, February, 63 pp.

Dolan, C., and LaFraugh, R. (1993). "High Strength Concrete in the Precast Concrete Industry," *PCI Journal*, V 38, No 3, May-June, pp. 16-19.

Domone, P., and Soutos, M. (1994). "An Approach to the Proportioning of High-Strength Concrete Mixes," *Concrete International*, V 16, No 10, October, pp. 26-31.

Fiorato, A. (1989). "PCA Research on High-Strength Concrete," *Concrete International*, V 11, No 4, April, pp. 44-50.

Kojundic, T. (1997). "HP Concrete Flexes its Muscles," *Roads & Bridges*, Vol. 35, No. 4, pp. 50-53.

Kosmatka, S. H. and Panarese, W. C. (1994). *Design and Control of Concrete Mixtures*, 13th Ed., Portland Cement Association, p. 170.

Lane, S.N., and Podolny, W. (1993). "The Federal Outlook for High Strength Concrete Bridges," *PCI Journal*, V 38, No 3, May-June, pp. 20-33.

Lessard, M., Chaallal, O., Aitcin, P. C. (1993). "Testing High-Strength Concrete Compressive Strength," *ACI Materials Journal*, Vol. 90, No. 4, July/August, pp. 303-308.

Moreno, J. (1990). "225 W. Wacker Drive," *Concrete International*, V 12, No 1, January, pp. 35-39.

Peterman, M., and Carrasquillo, R. (1986). *Production of High Strength Concrete*, Noyes Publications, Park Ridge, New Jersey, 278 pp.

Ralls, M.L., and Carrasquillo, R. (1997). "Texas High Performance Concrete Bridges Implementation Status," Proceedings of the *PCI/FHWA International Symposium on High Performance Concrete*, Precast/Prestressed Concrete Institute, October 20-22.

Russell, B. (1994). "Impact of High Strength Concrete on the Design and Construction of Pretensioned Girder Bridges," *PCI Journal*, V 38, No 4, July-August, pp. 76-89.

Smith, G., and Rad, F. (1989). "Economic Advantages of High-Strength Concretes in Columns," *Concrete International*, V 11, No 4, April, pp. 37-43.

Tikalsky, P., Carrasquillo, P., and Carrasquillo, R. (1988). "Strength and Durability Considerations Affecting Mix Proportioning of Concrete Containing Fly Ash," *ACI Materials Journal*, V 85, No 6, November-December, pp. 505-511.